Image Cover Sheet

CLASSIFICATION	SYSTEM NUMBER 507675
UNCLASSIFIED	

TITLE

REQUIREMENTS CAPTURE AND DESIGN ISSUES FOR A REAL-TIME DECISION SUPPORT SYSTEM FOR THE CANADIAN PATROL FRIGATE

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to:

DEFENCE RESEARCH ESTABLISHMENT
CENTRE DE RECHERCHES POUR LA DÉFENSE
VALCARTIER, QUÉBEC

DREV - R - 9629
Unlimited Distribution/Distribution illimitée

REQUIREMENTS CAPTURE AND DESIGN ISSUES FOR A REAL-TIME DECISION SUPPORT SYSTEM FOR THE CANADIAN PATROL FRIGATE

by

B. Chalmers, J. Roy, R. Carling, S. Paradis and É. Bossé

March/mars 1998

Approved by/approuvé par

Éloi Bossé
Section Head/Chef de section

12 mars 98
Date

WARNING NOTICE

The information contained herein is proprietary to Her Majesty and is provided to the recipient on the understanding that it will be used for information and evaluation purposes only. Any commercial use, including use for manufacture, is prohibited. Release to third parties of this publication or of information contained herein is prohibited without the prior written consent of DND Canada.

© Her Majesty the Queen in Right of Canada as represented by the Minister of National Defence, 1998

ABSTRACT

DREV initiated the Simulated Real-Time Environment (SRTE) project to investigate concepts and capture the real-time requirements of a decision support system that can provide enhanced capability within the Command and Control System to counter the current and anticipated future air and surface threat to the Canadian Patrol Frigate. Among its principal roles, this system will: continuously take in data from the ship's sensors and other information sources; support the formulation, maintenance and display of an accurate tactical picture derived by fusing all available data, and assist in the interpretation of this picture; and formulate and provide recommended courses of action for responding to anticipated or actual threats. This document describes both cognitive and technological aspects of the decision-aid approach that is a cornerstone of the SRTE project and gives a detailed technical description of the methodology and associated R&D work that is being conducted to capture system requirements.

RÉSUMÉ

Le CRDV a mis en place le projet d'environnement temps réel simulé (ETRS) dans le but d'étudier les concepts liés au design d'un système d'aide à la décision et d'en saisir les exigences et contraintes temporelles. Un tel système fonctionnant en temps réel permettrait d'améliorer la capacité du système de commandement et contrôle de la Frégate de patrouille canadienne à contrer la menace actuelle et future, qu'elle soit aérienne ou de surface. Le système d'aide à la décision aura comme fonctions principales: de saisir continuellement les données et les informations provenant des capteurs du navire et des sources externes; de fusionner toute l'information disponible dans le but de construire, maintenir et afficher une image tactique précise; d'assister l'usager dans l'interprétation de cette image; et de formuler et fournir des recommandations pour contrer la menace anticipée ou actuelle du navire. Ce document décrit les aspects cognitifs et technologiques de l'approche d'aide à la décision qui constitue la pierre angulaire du projet ETRS, et donne une description technique détaillée de la méthodologie et des travaux de recherche et développement en cours pour la saisie des exigences d'un tel système.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Technological advances in threat and sensor technology, the increasing tempo of warfare and the resulting complexity of combat operations for Above Water Warfare (AWW) create significant challenges to current and future shipboard systems and the operators who must use these systems to defend their ship and fulfill their mission. Potential combat scenarios can span intense, open-ocean warfare to highly uncertain, limited conflicts in littoral areas. In high-clutter, terrain-masked environments, establishing, classifying and identifying the numerous contacts, determining their intents, and generally resolving the large number of ambiguities in the situation picture, as well as taking appropriate action in a timely manner, will be very challenging tasks. There is a fundamental operational requirement for timely, effective response to this diverse range of threats.

The Data Fusion and Resource Management (DFRM) Group at the Defence Research Establishment Valcartier (DREV) has initiated the Simulated Real-Time Evaluation (SRTE) project to investigate solutions to this problem. Its purpose is to investigate concepts and capture the real-time requirements of a Decision Support System (DSS) that can provide enhanced capability within the Command and Control System (CCS) to counter the current and anticipated future air and surface threat to the Canadian Patrol Frigate (CPF). This system will: continuously take in data from the ship's sensors and other information sources; support the formulation, maintenance and display of an accurate tactical picture derived by fusing all available data (its Multi-Sensor Data Fusion capability), and assist in the interpretation of this picture (its Situation and Threat Assessment capability); and formulate and provide recommended courses of action for responding to anticipated or actual threats (its Resource Management capability). More specifically, this system includes an improved target surveillance and tracking capability and an improved Threat Evaluation and Weapon Assignment (TEWA) capability for the CPF.

This document describes both cognitive and technological aspects of the decision aid approach that is a cornerstone of the SRTE project and gives a detailed technical description of the R&D work that is being conducted to capture system requirements. A novel aspect is the development of an experimental capability for evaluating the performance and capturing the requirements of a complex, distributed real-time system. This involves the design of a high-performance simulation environment, called the Simulated Real-Time Environment (SRTE), for evaluating concepts, algorithms and architectures that may be applicable to the DSS.

LIST OF ACRONYMS

AAW		Anti-Air Warfare
AI	:	Artificial Intelligence
APAR	:	Active Phased Array Radar
ASCACT	:	Advanced Shipboard Command and Control Technology
ASM	:	Anti-Ship Missile
ASWC	:	Assistant Sensor Weapons Controller
AWW	:	Above Water Warfare
CASE	:	Computer-Aided Software Engineering
CASE_ATTI	:	Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification
C2	:	Command and Control
C2IS	:	C2 Information System
C3I	:	Command, Control, Communications and Intelligence
CCS	:	C2 System
CIC	:	Combat Information Center
CIO	:	Communications Intercept Operator
CIWS	:	Close-In Weapon System
CO	:	Commanding Officer
COTS	:	Commercial Off-The-Shelf
CPF	:	Canadian Patrol Frigate
CPU	:	Central Processing Unit
CRAD	:	Chief Research and Development
CRDV	:	Centre de recherches pour la défense Valcartier
CSTC	:	Combat Systems Test Center
CSTSF	:	Combat Systems Test and Support Facility
DEFTT	:	Decision Making Evaluation Facility for Tactical Teams

DF	:	Data Fusion
DFRM	:	Data Fusion and Resource Management
DMSS	:	Directorate Maritime Ship Support
DND	:	Department of National Defence
DNR	:	Directorate Naval Requirements
DoD	:	Department of Defence
DRDB	:	Defence Research and Development Branch
DRE	:	Defence Research Establishment
DREO	:	Defence Research Establishment Ottawa
DREV	:	Defence Research Establishment Valcartier
DSAM	:	Deputy Scientific Advisor Maritime
ECM	:	Electronic Countermeasures
EMCON	:	Emission Control
ESM	:	Electronic Support Measures
EWS	:	Electronic Warfare Supervisor
HCI	:	Human-Computer Interface
ID	:	Identification
IEEE	:	Institute of Electrical and Electronic Engineers
IFF	:	Identification Friend or Foe
I/O	:	Input/Output
IR	:	Infrared
IRST	:	Infrared Search and Track
JOTS	:	Joint Operational Tactical System
KBS	:	Knowledge-Based System
LAN	:	Local Area Network
LRR	:	Long Range Radar
MCOIN	:	Maritime Command Operational Information Network
MFR	:	Multi-Function Radar
MHT	:	Multiple Hypothesis Tracking
MOE	:	Measure of Effectiveness
MOP	:	Measure of Performance
MRR	:	Medium Range Radar

MSDF	:	Multi-Sensor Data Fusion
MTP	:	Maritime Tactical Picture
NETE	:	Naval Engineering Test Establishment
OODA	:	Observe-Orient-Decide-Act
ORO	:	Operations Room Officer
R&D	:	Research and Development
RISC	:	Reduced Instruction Set Computer
RM	:	Resource Management
RT	:	Radar Tracker
RTE	:	Run-Time Executive
RTS	:	Real-Time System
SAM	:	Surface-to-Air Missile
SA	:	Situation Awareness
SDTF	:	Software Development and Test Facility
SHINPADS	:	Shipboard Integrated Processing and Display System
SME	:	Subject-Matter Expert
SRTE	:	Simulated Real-Time Environment
STA	:	Situation and Threat Assessment
STIR	:	Separate Track and Illumination Radar
SWC	:	Sensor Weapons Controller
TA	:	Threat Assessment
TADMUS	:	Tactical Decision Making Under Stress
TEWA	:	Threat Evaluation and Weapon Assignment
TRUMP	:	Tribal class Update and Modernization Project
TS	:	Track Supervisor
USN	:	US Navy
WAP	:	Wide Area Picture
WATS	:	Wide Area Tactical Situation
WEM	:	Weapon Engagement Manager

1.0 INTRODUCTION

Technological advancements in threat and sensor technology, the increasing tempo and diversity of warfare scenarios and the resulting complexity of combat operations for the Above Water Warfare (AWW) are creating significant challenges to current and future shipboard systems and the operators who must use these systems to defend their ship and fulfill their mission.

For example, new developments in missile technology are leading to reduced detection ranges and reaction times against anti-ship missile (ASM) threats and a need for increased defensive missile performance against these threats. Development trends for the cruise missile threat include smaller signatures and lower/higher altitudes, higher speeds and high-acceleration manoeuvres, radiation control and multimode guidance, hardening and relocation of vulnerable components, and coordinated attack times (Ref. 1). The continuing evolution of shipboard sensors, as well as the growing need of naval commanders to access non-organic information from a wide variety of external sources, is increasing the volume, rate and complexity of information that needs to be coherently integrated into the Maritime Tactical Picture (MTP) of their battle space.

Potential naval combat scenarios can now span the range from open-ocean warfare to regional or limited conflicts in littoral or near land areas (Ref. 1). Littoral areas are frequently characterised by confined and congested water and air space occupied by friends, adversaries, and neutrals (Ref. 2). In the high-clutter, terrain-masked environment of such scenarios, establishing, classifying, and identifying the numerous contacts, determining their intents, and generally resolving the large number of ambiguities in the situation picture, as well as taking appropriate action in a timely manner, will be very challenging tasks for combat system operators. Scenarios can involve air attacks from sophisticated, fast ASMs fired from air, surface or subsurface platforms, at closely spaced arrival intervals. Scenarios can also

evolve in ways that involve transitions among a variety of situation contexts, varying in levels of information uncertainty and threat intensity. For example, a relatively unrestricted engagement in an open-ocean scenario may suddenly develop highly uncertain aspects when interactions with neutrals become embedded within the engagement. There is a fundamental operational requirement for timely, effective response in the face of such threats.

While current and anticipated developments in the combat environment of the AWW undoubtedly call for continuing improvements in weapon and sensor technology for naval defence, there are, however, other important areas where advancements hold the promise of even more direct payback. Our concern in the R&D program described in this document is with the areas of automated data fusion and decision and action support, and their integration at the shipboard level, as a means of responding to new and emerging challenges for the AWW. These areas have significant potential for effecting improvements in the ship's Command and Control System (CCS) that support combat system operators in executing their increasingly complex and demanding tasks. Potential benefits include improvements in:

- the utilization of existing weapon and sensor systems;
- the capability to identify, integrate, comprehend, and manage a larger sphere of tactically significant information from both organic and non-organic sources, leading to enhanced situation awareness;
- the capability to optimise decision-making performance in a very stressful environment; and
- the support for action implementation once a decision to act has been made and the action is being carried out.

Research and Development (R&D) activities by the Data Fusion and Resource Management (DFRM) Group at the Defence Research

Establishment Valcartier (DREV) are aimed specifically at investigating system integration concepts for providing automated support for various Command and Control (C2) processes dealing with data and information management and tactical decision making and action implementation at the shipboard level. The group has developed an approach to help counter the anticipated threat to our surface ships by increasing the AWW defence capability of HALIFAX Class ships, also known as Canadian Patrol Frigates (CPFs), through the development of a real-time, embedded Decision Support System (DSS) that interacts in a variety of operational modes with combat system operators to support the tactical decision making and action execution processes in a ship's Operations Room. Among its principal roles, this DSS will:

- continuously take in data from the ship's sensors and other information sources;
- support the formulation, maintenance and display of an accurate dynamic tactical picture of the AWW derived by fusing all available data, and thereby assist in the interpretation of the evolving tactical situation;
- formulate and provide recommended courses of action for responding to anticipated or actual threats, including, as necessary, options to defend the ship using the best possible combination of hardkill and softkill weapons or other defensive means;
- present all necessary information to enable the Commanding Officer (CO) and AWW team to decide on a course of action in a timely manner; and
- coordinate and direct action implementation once a decision to act has been made and an action is being carried out.

The DSS will be an embedded component of the ship's combat system, integrated within the CCS, that provides real-time implementations of functions for Multi-Sensor Data Fusion (MSDF), Situation and Threat

Assessment (STA), and Resource Management (RM). In view of the functional integration involved, we call this sub-system of the ship's CCS an MSDF/STA/RM system.

The current primary focus of the DFRM Group's R&D is to support an investigation of functionality and performance enhancements to the CCS in the areas of information collection and information evaluation, focusing specifically on data fusion and resource management decision aiding, within the scope of the mid-life upgrade of the CPF expected in the Frigate Life Extension (FELEX) Program in the 2005-2015 time-frame. Such enhancements are in accordance with operational capability requirements for at sea Command and Control Information Systems (C2ISs) as promulgated by Maritime Command in CFCD 117, Vol. II (Ref. 3). However, despite the focus on the CPF platform, it is important to note that the approach being pursued aims at the same time to be sufficiently generic, comprehensive, and flexible to permit its adaptation, further development and refinement, as well as the application of its techniques and results, to current or future R&D programs for other platforms. This has the concomitant advantage of reducing the cost of any potential follow-on work (e.g., for evaluating evolutionary improvements to the CCS of the IROQUOIS Class destroyers or determining CCS requirements for the expected replacement of this class of ship in the next century).

To develop the decision-aid approach described above, many R&D investigations in the areas of shipboard Multi-Sensor Data Fusion, Situation and Threat Assessment and Resource Management have been conducted over the last few years by the DFRM Group at DREV and its contractors and collaborators (from both industry and university). Analyses and demonstrations of different MSDF, STA and RM approaches, algorithms and techniques for the CPF (Ref. 4) have been carried out. These investigations have already established a significant technological base by addressing a broad range of issues concerning the application of MSDF, STA and RM technologies to the CPF. However, they have approached the problem in an essentially discrete, bottom-up manner. MSDF has focused on analysing,

developing and evaluating advanced techniques to automatically produce the optimal estimate of the position, kinematic behaviour, and identification of all objects surrounding a single ship, mainly through the fusion of data from dissimilar organic sensors, while including non-organic information. STA has been concerned with providing reliable assessments of the tactical situation in which the ship is operating that are important for the successful accomplishment of the mission. RM has aimed to provide planning and decision support functionality in the CCS to aid military personnel in the integrated use of critical defence resources and to manage their coordination in accordance with such decisions.

This previous research has provided certain important pieces of the puzzle. However, there are other critical pieces which still need to be added to complete the picture of an integrated MSDF/STA/RM-based decision support system. Missing pieces include various techniques and methods which are not yet fully understood for implementation on the CPF, or techniques and methods that are understood, but their real-time implementations have not yet been proven. Of note also is that STA and RM investigations are relatively more recent and less mature compared with those of MSDF. This disparity is not too surprising, however, since it reflects the general state of research worldwide in the various technology areas.

Moreover, studies in MSDF, STA and RM have been performed as a number of separate projects and a complete DSS for the CCS integrating MSDF, STA and RM techniques and methods in a real-time system cannot yet be demonstrated.

Finally, although a preliminary examination of cognitive systems engineering issues for the design of the DSS is already ongoing at DREV, a more extensive study remains to be undertaken. Important issues that need further examination include:

- various automation approaches (e.g., functional/task allocation and the apportioning of decision-making control between the human and the

automated system);

- the content, structure and form of interactions between the DSS and combat system operators of the Operations Room via the user interface to the DSS; and

- a detailed analysis of models of human decision making that can form the basis for human-machine interaction.

Broadening the scope of the work to more adequately address such cognitive systems engineering issues adopts a user-centred perspective to the design of the DSS. This is aimed at developing a comprehensive understanding of how computational power, as it relates to providing MSDF, STA and RM processing capabilities, can be most effectively deployed to enhance the operational effectiveness of combat system operators in the face of the current and anticipated AWW threat.

In parallel then with continuing efforts within the DFRM Group to effect refinements and improvements in the individual processes, an important new research focus has emerged recently, aimed at addressing MSDF/STA/RM integration problems in a top-down manner and evaluating potential solutions. This investigation is being conducted in a new R&D project known as the Simulated Real-Time Evaluation (SRTE) project.

The principal purpose of this document is to identify and give a technical description of the R&D work that is being conducted in the SRTE project. Accordingly, this document provides a foundation for the technical activities of the project and presents the DFRM Group's view of the project at the time of its conception. Since the project's R&D results are intended to support an investigation of enhancements to the CCS of the CPF, the document also briefly reviews the CPF C2IS development philosophy, first presented in Ref. 4, and identifies the place of the SRTE project in the tools/activities loop for scientists, engineers and operators involved in the development or acquisition of integrated C2IS components for the CPF.

Finally, to help bring into sharper focus the decision-aid approach that is a cornerstone of the SRTE project, this document gives a preliminary review of some of the cognitive systems engineering issues that arise in the design of the DSS. In the process it touches, albeit incompletely, on a number of areas where further cognitive systems research is needed if the results of the current project are to reach maturity in a prototype realization of an integrated MSDF/STA/RM DSS for the CPF.

The layout of this document is as follows. Chapter 2.0 briefly reviews the CPF C2IS development philosophy with which the aims of the SRTE project are consistent. It also provides a high-level description of the data fusion and resource management C2 processes that are being investigated for integration within an MSDF/STA/RM-based decision support system.

Chapter 3.0 is devoted to exposing some of the cognitive issues germane to the development of an MSDF/STA/RM system. Chapter 4.0 provides an overview of the details of the SRTE project. First, the context and role of this work are established. The discussion centres on extending previous R&D efforts at DREV aimed at investigating MSDF, STA and RM processes and on significantly enhancing DREV's current capability to provide consulting services concerning envisioned functionality and performance enhancements to the CCS in data fusion, and information evaluation and resource management decision aiding, as part of the mid-life upgrade of the CPF expected in the FELEX program. The four major technical activities of the project are then identified.

The first activity of the SRTE project is concerned with establishing a methodology for the specification and design of a generic real-time MSDF/STA/RM system and a framework for integrating MSDF, STA and RM functions. The technical details of this activity are described in Chapter 5.0.

The details of the work in the second activity toward designing and implementing a novel, high-performance simulation environment to permit capturing the real-time requirements of the automated components of an

MSDF/STA/RM system are given in Chapter 6.0. This environment provides an important capability for accomplishing the work in the remaining two activities of the project.

The design of a baseline MSDF/STA/RM system is the subject of the third activity and its details appear in Chapter 7.0. The objective here is to develop an integrated real-time system that would provide an enhanced CCS for the CPF, with an improved target surveillance and tracking capability and an improved Threat Evaluation and Weapon Assignment (TEWA) capability.

Chapter 8.0 discusses work in the fourth activity that investigates refinements and extensions to multiple platform defence scenarios and captures the real-time requirements of an MSDF/STA/RM system suitable for such scenarios. Finally, Chapter 9.0 presents conclusions.

The research and development activities leading to the production of this document were performed at DREV between November 1994 and October 1996, first under PSC 12C, Ship Combat System Integration, and later under Thrust 1a, Integrated Naval Above Water Warfare and Shipboard Command and Control, and Thrust 1b, Maritime Command, Control, Communications and Intelligence. This work was conducted for Project 1ba, Shipborne C3I, and is specifically part of Work Unit 1ba12, entitled "Investigations of MSDF/STA/RM Concepts".

2.0 BACKGROUND

As mentioned in Chapter 1.0, the Simulated Real-Time (SRTE) project is investigating various concepts for the development of a decision support system (DSS), called an MSDF/STA/RM system, to support tactical decision making and action execution in the Operations Room of the CPF. This DSS will provide integrated real-time implementations of functions for MSDF, STA, and RM. Importantly, the results of this technical investigation are expected to significantly enhance DREV's capability to provide consulting services concerning envisioned functionality and performance enhancements to the CCS in data fusion, and information evaluation and resource management decision aiding, as part of the mid-life upgrade of the CPF expected in the FELEX Program.

To situate the context of the SRTE project and to provide a better understanding of its role in the general R&D process, this chapter gives a brief review of the more global CPF C2IS development philosophy with which the aims of the SRTE project are consistent. It also provides a high-level description of the data fusion and resource management C2 processes that are being investigated for integration within an MSDF/STA/RM DSS. The reader is referred to Ref. 4 for a recent review and status report of DREV's R&D in the areas of MSDF, STA and RM applied to shipboard C2.

2.1 CPF C2IS Development Philosophy

A naval CCS, as found in the CPF, is a very complex system. It is not surprising, therefore, that its enhancement to satisfy new operational requirements raises a number of broad and far-reaching issues that require significant R&D for their resolution. For example, these issues touch on complex problems in real-time systems design that require extensive exploratory and empirical analyses, as well as studies that range from the evaluation of theoretical concepts (using very simple computer simulations supporting rigorous mathematical analyses) all the way to the actual testing

of prototypes during live military exercises (i.e., live ship trials). Hence, part of the overall shipboard C2IS analysis, design, development and evaluation process involves the decision regarding the most appropriate approach or means that will be used for conducting these R&D activities. A characterization of this broad spectrum of possible tools and approaches is shown in Fig. 1. Generally, as depicted in Fig. 1, there are tradeoffs in selecting one approach over the other. The most obvious one is probably the level of operational realism obtained versus the cost.

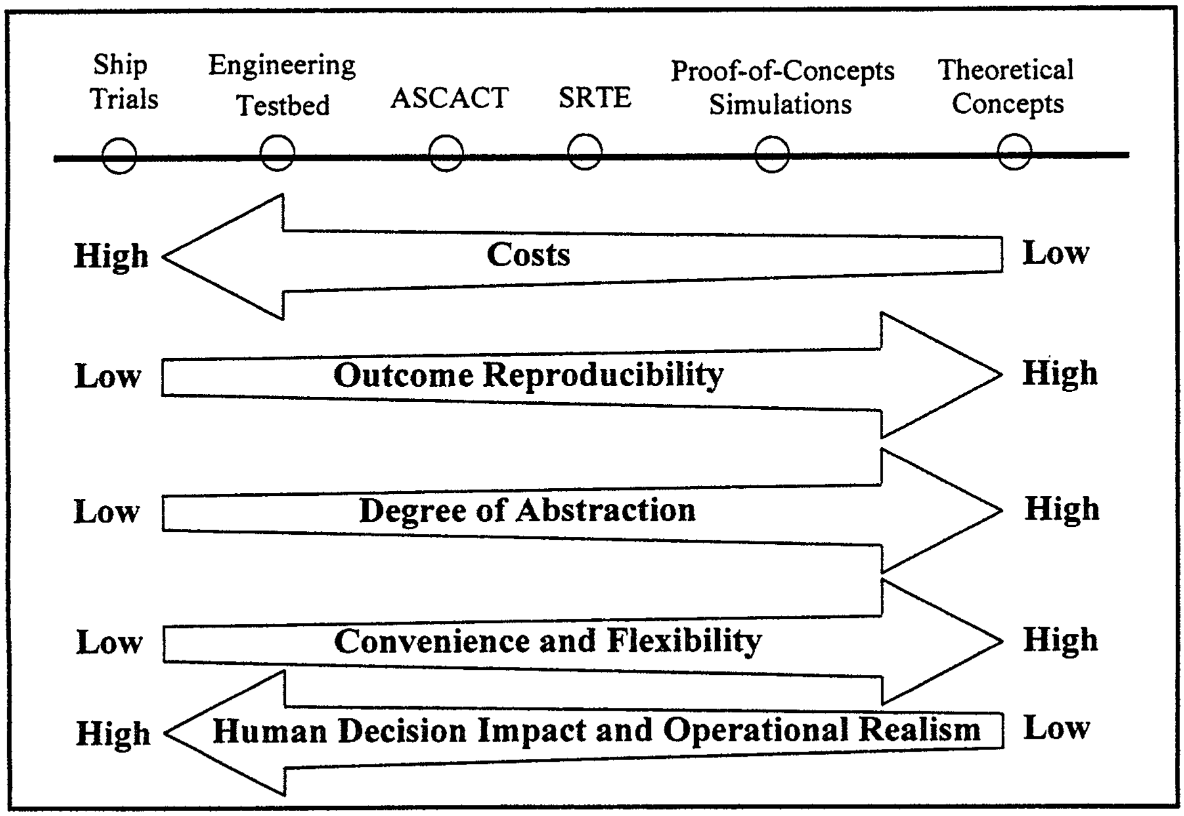

FIGURE 1 - Tradeoffs in analysis, modelling and evaluation approaches for shipboard C2IS

Evidently, the ultimate test to evaluate the military value of a C2IS prototype would be to use it in live military exercises. Such an environment provides reasonably high fidelity operational conditions since the real-world physics, human, equipment and tactics/doctrine can be fully taken into

account. However, there are drawbacks to this approach. The system designers typically cannot have full control of the events, and it is difficult to collect the relevant data. For example, precise truth data that are needed for MSDF performance evaluation can be difficult to obtain in real-world tests; however, these are readily available in computer simulations. The latter typically constitutes very controlled research environments that offer a high level of convenience and flexibility at low cost. Unfortunately, digital simulations cannot always adequately represent complex real-world phenomena and human behaviour. Specialised field data collection campaigns can be a good compromise between these two extremes. Indeed, this approach is often used to validate computer simulations. However, such trials can rapidly become very costly.

Given the broad scope and complexity of issues raised in the enhancement activities under consideration for the CPF C2IS, no single tool or activity can realistically be expected to provide the Department of National Defence (DND) with all the required answers. Hence, the R&D process needs to proceed incrementally and iteratively. In addition, the R&D environment for investigating and evaluating individual CPF C2IS components, and their integration, must provide an assortment of compatible tools and testbeds that map to various points on the tradeoff spectrum identified in Fig. 1. This process starts with conceptual R&D whose results are then evaluated in proof-of-concept simulations on DREV-based testbeds. These testbeds provide controlled environments for experimental purposes. Promising concepts subsequently become candidates for initial real-time implementation and experimentation in the Advanced Shipboard Command and Control Technology (ASCACT) testbed (Ref. 4) and later in some combination of ASCACT and a shore-based system using the Shipboard Integrated Processing and Display System (SHINPADS) bus (such as the Combat Systems Test Centre (CSTC), Software Development and Test Facility (SDTF) or the Engineering testbed being proposed by Directorate Maritime Ship Support (DMSS) 8 (Ref. 4)) for advanced development and preliminary human-in-the-loop assessments. Finally, high-fidelity live shipboard trials are conducted, which also provide further user feedback.

Upon successful completion of this final step, the research activity may then be used to develop a final version for incorporation in the CPF. Figure 2 illustrates this entire R&D process. It shows the expected tools and activities loop, also known as the "R&D Path to the Ship", for scientists, engineers and operators involved in the development and/or acquisition of shipboard C2IS components for the CPF.

The R&D process for the CPF CCIS will undoubtedly require several iterations in the tools and activities loop, illustrated below in Fig. 2, where the results of one iteration lead to refinements, extensions and improvements in the next iteration. Notably, this is compatible with a spiral approach to systems engineering. It is evident that progress in this R&D process will both impact and be impacted by naval requirements (i.e., the customer must be kept involved during this iterative process) and that this interaction may subsequently even help in shaping naval doctrine.

In summary, the "R&D Path to the Ship" represents a focused, evolutionary and incremental approach to conducting applied R&D, starting with conceptual, exploratory work in a Defence Research Establishment (DRE), that aims at resolving identified naval requirements in a way that mitigates the risk of the R&D and increases the chance of ultimately successful delivery of an end product to the ship.

Finally, we note that the role of the SRTE project in the R&D process described above is twofold. First, it continues DREV's previous technical investigations aimed at automating various C2 processes for MSDF, STA and RM, and focuses, for the first time, on assessing their real-time requirements, both separately and within a framework for their integration in an embedded DSS that provides data and information management functions and tactical decision making and action implementation support as part of the ship's CCS; and second, it designs and implements a novel, high-performance simulation environment to permit proof-of-concept simulations for capturing and analysing these real-time requirements.

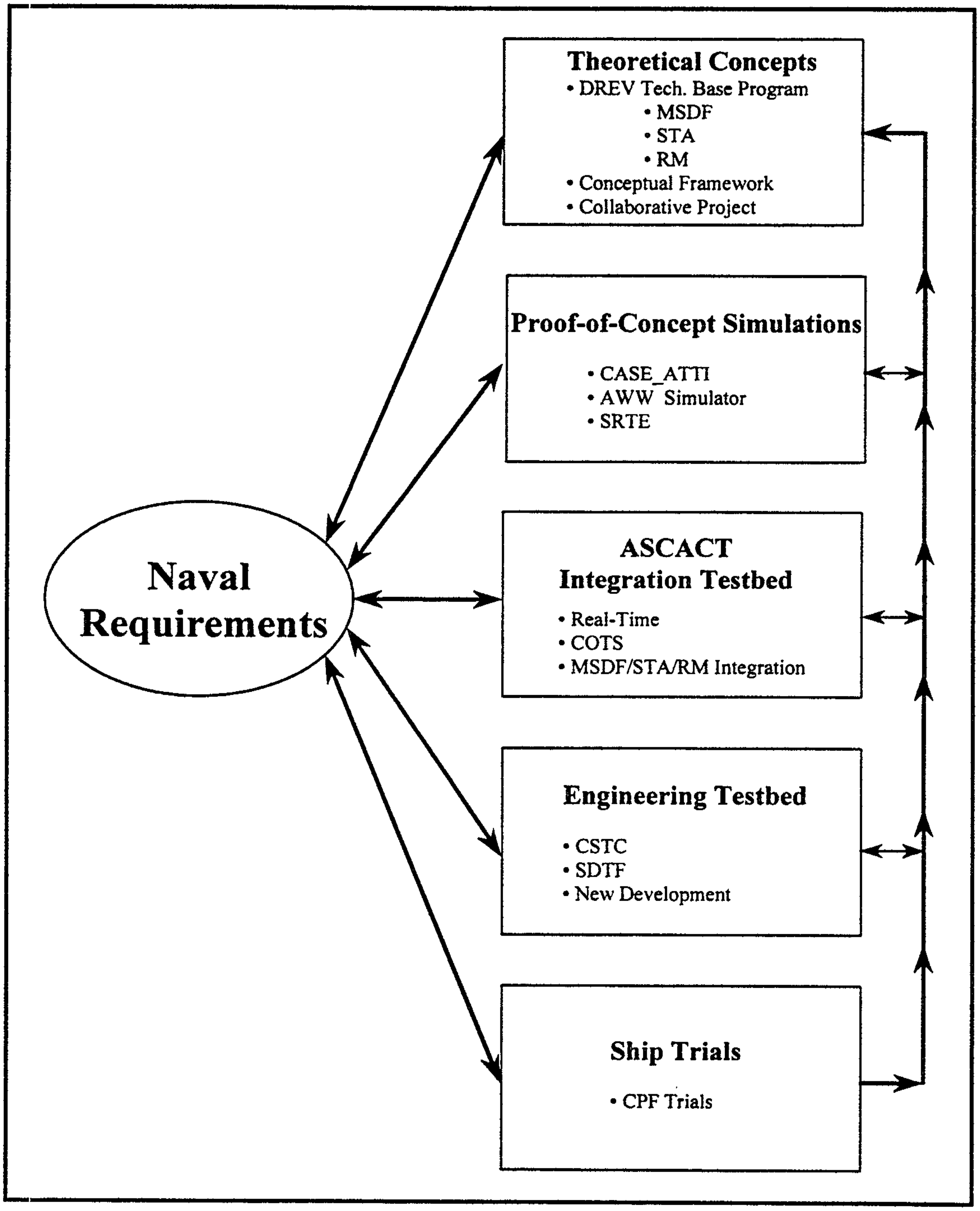

FIGURE 2 - Tools and activities loop for scientists, engineers and operators involved in the development and/or acquisition of shipboard C2IS components for the CPF

2.2 Definitions of MSDF, STA, and RM

2.2.1 Data Fusion Definition

Throughout the 1980s, the three U.S. military services pursued the development of tactical and strategic surveillance systems employing data fusion and supported extensive research in the areas of target tracking, target identification, algorithm development for correlation (association) and classification, and the application of intelligent systems to situation assessment (Ref. 5). The large amount of fusion-related work in this period raised some concern over possible duplication of effort. As a result, the Joint Directors of U.S. Department of Defense (DoD) Laboratories (JDL) convened a Data Fusion Subpanel to (1) survey the activities across all services, (2) establish a forum for the exchange of research and technology, and (3) develop models, terminology and a taxonomy of the areas of research, development and operational systems.

As a result of many years of effort to establish standardization and stability in the lexicon of data fusion, the definition of many terms is slowly achieving consensus across the diversified application community (Ref. 6). Problem-specific nuances in these definitions remain but agreement on a meaningful subset of terms does seem to exist, providing an important basis for communication across specialised research groups.

Data fusion is fundamentally a process designed to manage (i.e., organise, combine and interpret) data and information, obtained from a variety of sources, that may be required at any time by operators and commanders for decision support. The sources of information may be quite diverse, including sensor observations, data regarding capability and availability of targets, topographic and environmental data, and information regarding doctrine and policy. The data and information provided by these various sources may contain numbers of targets, conflicting reports, cluttered backgrounds, degrees of error, deception, and ambiguities about events or behaviours.

In this context, Data Fusion (DF) is an adaptive information process that continuously transforms the available data and information into richer information, through continuous refinement of hypotheses or inferences about real-world events, to achieve:

- refined (and potentially optimal) kinematic and identity estimates of individual objects; and

- complete and timely assessments of current and potential future situations and threats (i.e., contextual reasoning), and their significance in the context of operational settings.

The process is also characterised by continuous refinements of its estimates and assessments, and by evaluation of the need for additional data and information sources, or modification of the process itself, to achieve improved results.

2.2.2 Data Fusion Hierarchy

The process of data fusion may be viewed as a multi-level, hierarchical inference process whose ultimate goal is to assess a mission situation and identify, localise and analyse threats. However, not every data fusion application is responsible for all of these outputs. Some applications are only concerned with the position and identification of objects. Others are primarily oriented to the situation and how it is evolving. Still others focus on the threat and its possible impact on achieving mission objectives. In addition, data fusion can be responsible for identifying what information is most needed to enhance its products and what sources are most likely to deliver this information.

Given these considerations, a complete data fusion system can typically be decomposed into four levels:

Level 1 - Multi-Sensor Data Fusion (MSDF);

Level 2 - Situation Assessment (SA);

Level 3 - Threat Assessment (TA); and

Level 4 - Process Refinement Through Resource Management (RM).

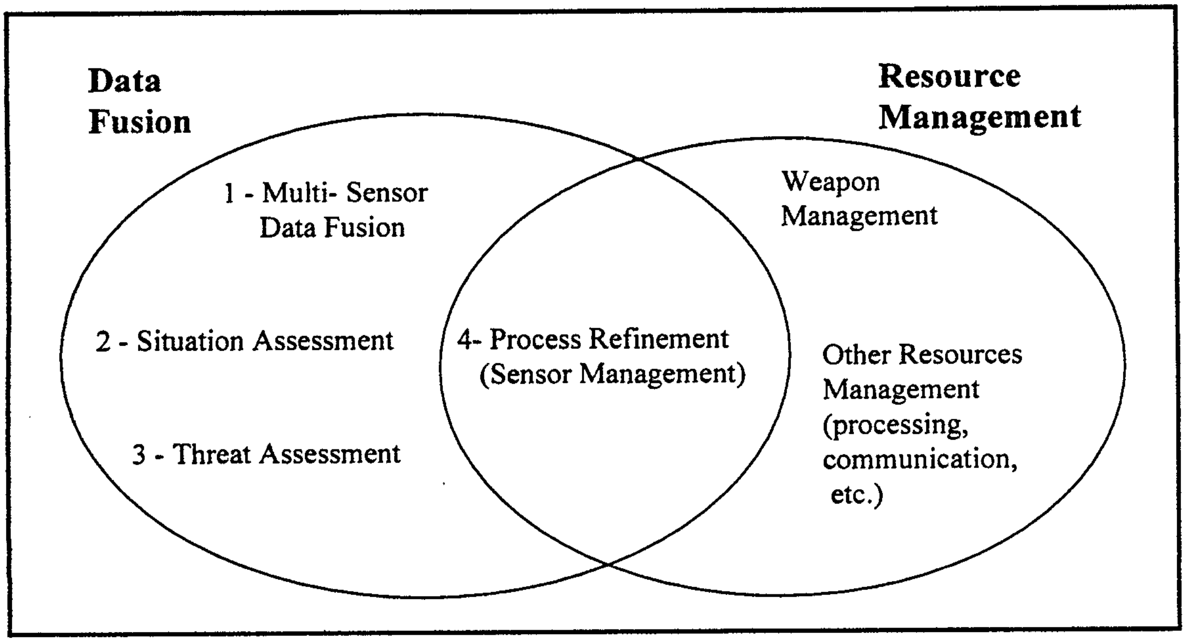

FIGURE 3 - Overlap between the data fusion and resource management domains

Each succeeding level of data fusion processing deals with a higher level of abstraction. Level 1 data fusion uses mostly numerical, statistical analysis methods, while levels 2, 3 and 4 data fusion use mostly symbolic Artificial Intelligence (AI) methods. Note that resource management in the context of level 4 fusion is mainly concerned with the information gathering process refinement (i.e., sensor management). It is important to note, however, that the overall domain of resource management also encompasses the management of weapon systems and other resources. Figure 3 illustrates the overlap between the data fusion and resource management domains.

2.2.2.1 Level 1 - Multi-Sensor Data Fusion

Multi-sensor data fusion (MSDF) is concerned solely with individual objects, first in associating the sensor outputs with specific known objects or using them to initiate new objects. Level 1 processing uses sensor data to correctly and quickly derive the best estimates of current and future positions for each hypothesised object. In addition, inferences as to the identity of the objects and key attributes of the objects are developed.

Key MSDF functions include: data alignment, data association/correlation, kinematic data fusion, target state estimation, target kinematics behaviour assessment, target identity information fusion and track/cluster management.

2.2.2.2 Level 2 - Situation Assessment

Based on incomplete and inaccurate sets of data and information, situation assessment (SA) is devoted to the continuous inference of statements about the hypothesised objects provided by the lower level data fusion function in order to derive a coherent, composite tactical picture of the situation. This picture must be described in terms of groups or organizations of objects so that enemy intent can be estimated in the next higher level and decisions can be made by decision makers about how to use war fighting assets.

SA deals with monitoring and short-term or immediate situation diagnosis. Hence, SA consistently matches hypothesised objects with known and expected organizations and events, while conforming to terrain, enemy tactics and other warfare constraints, to develop a description or interpretation of the current relationships among these objects and events in the context of the operational environment. The result of this processing is a determination or refinement of the battle/operational situation.

Based on the situation abstraction products and information from technical and doctrinal databases, SA also attempts to anticipate future events over a short time horizon.

Key SA functions include: object aggregation, event/activity aggregation, contextual interpretation/fusion and multi-perspective assessment.

2.2.2.3 Level 3 - Threat Assessment

Threat assessment (TA) is concerned with the details necessary for decision makers to reach conclusions about how to position and commit the friendly forces. It can be viewed as a longer term diagnosis function to determine problems in the current situation and identify opportunities for taking corrective actions.

By coupling the products of situation assessment with the information provided by a variety of technical and doctrinal databases, TA develops and interprets a threat-oriented perspective of the data to estimate enemy capabilities and lethality, identify threat opportunities in terms of the ability of own force to engage the enemy effectively, estimate enemy intent (i.e., provide indications and warnings of enemy intentions), and determine levels of risk and danger.

Hence, TA uses the situation picture from level 2 and what is known about the enemy doctrine and objectives to predict the strengths and vulnerabilities of the threat forces and friendly forces. In addition, the friendly mission and specific options available to decision makers are tested within these strengths and vulnerabilities to guide decision making.

Key TA functions include: enemy forces capability estimation, prediction of enemy intent, identification of threat opportunities, multi-perspective assessment and offensive/defensive analysis.

2.2.2.4 Level 4 - Process Refinement (Resource Management)

Information resource management, level 4 processing, closes the data fusion loop by first examining and prioritizing what is unknown in the context of the situation and threat and then developing options for collecting this information by cueing the appropriate sensors and collection sources.

2.2.3 Resource Management Definition

Situation and threat assessments, together with command team interactions, as required and as response time permits, is used to drive the planning and decision support functions for allocating and scheduling the use of critical defence resources and coordinating response actions in support of the mission. Determination of the various options for use of the resources and the selection of the best course of action in a given situation is known as Resource Allocation. Resource Management refers to the continuous process of planning, coordinating and directing the use of the ship or force resources to counter the threat. It is therefore concerned with issues of both command and control.

3.0 REAL-TIME DECISION SUPPORT FOR SHIP-BASED AWW

Providing combat system operators in the Operations Room of the CPF with automated, real-time decision support for the AWW raises a host of technological and cognitive issues that require careful consideration. Technological issues address the hardware and software aspects of automating the information processing, decision analysis and control capabilities of the embedded support system. Cognitive issues are concerned with the specifics of the various cognitive-level behaviours (e.g., perception, monitoring, planning, problem solving and decision making) which the decision support system must exhibit and/or support for its users and the modes of human-computer interaction between these users and the automated system via a human-computer interface (HCI), including the content, structure and form of such interactions.

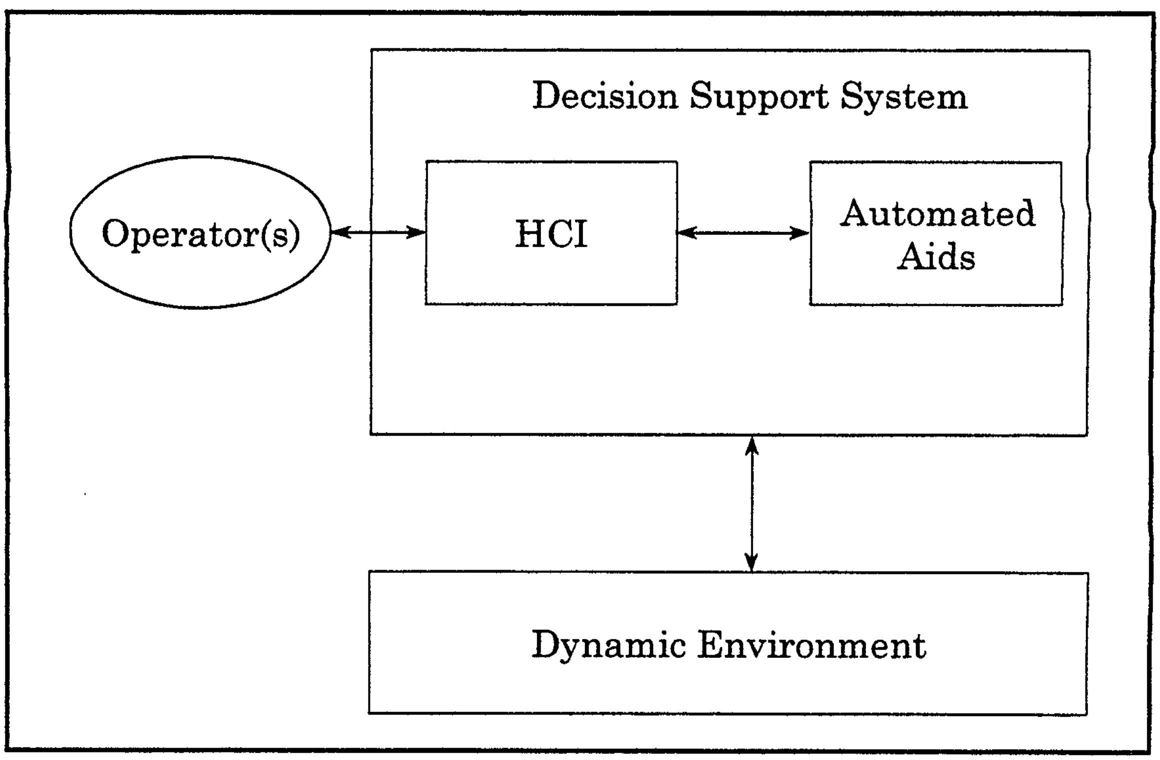

FIGURE 4 - Architecture of a general real-time decision support system (DSS)

A general real-time decision aiding architecture is shown in Fig. 4. Only high-level components are represented. The HCI component of the DSS mediates between an operator's perceptual, cognitive and motor systems and a dynamic environment with which he/she interacts, while the automated aids provide the processing tools that serve to facilitate and enhance his/her decision making about courses of action in response to events occurring in real time in the environment.

With respect to an MSDF/STA/RM DSS for Operations Room operators in the CPF, the environment is made up of two parts. The first part, internal to the ship, includes the various other hardware and software components of the ship's combat system, which is comprised of a number of systems, including the CCS, weapon systems, sensor systems and navigation systems. In the current conception, the MSDF/STA/RM system would become an embedded component of an enhanced CCS, within the ship's combat system. The second part of the environment consists of all entities external to the ship that are (or become) tactically significant over the course of the ship's mission, e.g., participating units, neutrals and threats. Together, these entities constitute a dynamic system whose behaviour evolves in real time in a manner that can depend on more than just its inputs due to the presence of autonomous and semi-autonomous entities in this system. Effectively, operators have to keep up with, or even better, keep ahead of, and respond to significant events occurring in the highly dynamic environment.

Since the ultimate goal must be to engineer a joint cognitive system, comprised of both humans and machines, that optimises the overall performance of the combined system, leading to improved operational effectiveness, in reality, technological and cognitive issues in the design of an MSDF/STA/RM DSS need to be considered together, from an ecological, holistic perspective (Ref. 7). This overall performance emerges from interactions of humans with the external AWW environment, with the aid of the DSS, as technology dictates what users can do and as users exploit the decision support tools that technology provides as aids in achieving their mission. It has been suggested, for example, that when tools dominate,

rather than constrain, the joint cognitive system, the system designer runs a strong risk of solving the wrong problem, and of creating new problems in the process (Refs. 8-9). Certainly, the literature provides a number of examples in other domains, including the airline cockpit and process control automation domains, where failures have been associated with a technology-centred approach to automation at the expense of cognitive issues (see, for example, Refs. 10-11). In other words, design of the MSDF/STA/RM DSS needs to adopt a human-environment system perspective; it must address both tool building and tool use if a successful joint human-machine cognitive system is to be achieved. Moreover, failure to do this at the outset, at the conceptual analysis and design stage, or proceeding from a solely technologically-centred perspective, runs the risk of designing a system that forces users to adopt procedures and strategies that might in the end degrade, instead of enhance, total performance because of the resulting cognitive dissonance between the human and the automated system.

It must be acknowledged that a successful MSDF/STA/RM system design, in addition to improving total mission performance, may well lead ultimately to a number of significant changes in procedures and practices in the ship's Operations Room. There is potential for impact on naval doctrine and on the roles of operators as currently practised in the CPF. In fact, it is very likely that the introduction of such technology as part of an augmented functionality of the ship's CCS will necessitate a significant re-evaluation of combat system operator organization and Operations Room layout, as well as operator requirements and tasks within this organization. However, while the present R&D project should provide valuable information that is useful in examining such issues, such an examination is outside the scope of this technical investigation.

This chapter is devoted to exposing some of the cognitive issues germane to the development of an MSDF/STA/RM DSS. The primary aim is to bring into sharper focus the decision aid approach that is a cornerstone of the SRTE project. In the course of the discussion, several cognitive issues are touched on that require additional research if the results of the SRTE project

are to reach maturity in a prototype realization of an integrated MSDF/STA/RM DSS for the CPF. The point of drawing attention to these latter issues is to provide the reader additional perspective on the extremely wide scope of the R&D work that is involved or required for the design of the DSS. In fact, a comprehensive study of systems engineering issues that examines technological and cognitive issues jointly, with a view, for example, to modelling human expertise, competence and performance, and using this knowledge to define a model of cooperation between human decision makers and the automated system, including capturing cognitive system requirements from the perspective of potential future users of the DSS, is an important area where further R&D work is required. Technological DSS issues that are specifically part of the R&D work in the SRTE project are elaborated in Chapters 5.0 to 8.0.

To provide the necessary background and context, this chapter begins by briefly examining various characteristics of the AWW environment that can be expected to impose significant perceptual and cognitive processing demands on combat system operators. CPF operational specifics are used throughout to ground this exposition.

3.1 Decision-Making Environment of Ship-Based AWW

Within the CPF, all tactical decision making for the AWW (as well as for the other warfare areas) is done in the ship's Operations Room. Within this windowless room, a team of operators interact with the ship's CCS through tactical display consoles with the aid of a number of other systems, perceive and interpret the information available from own-ship sensors and information data-linked from other co-operating platforms, and plan and conduct operations to meet the objectives of their mission. Their major C2 tasks include: weapon and sensor systems control, threat evaluation, weapon selection, navigation and ship manoeuvres, and mission planning and evaluation. The Operations Room team is supported in its activities by several other teams, external to the Operations Room, who are responsible for logistics, damage control, etc.

The ship's command structure is organised hierarchically, with various team members performing specific functions within various levels in the chain of command. The current combat system operator organization is shown in Fig. 5 where only the AWW is fully represented.

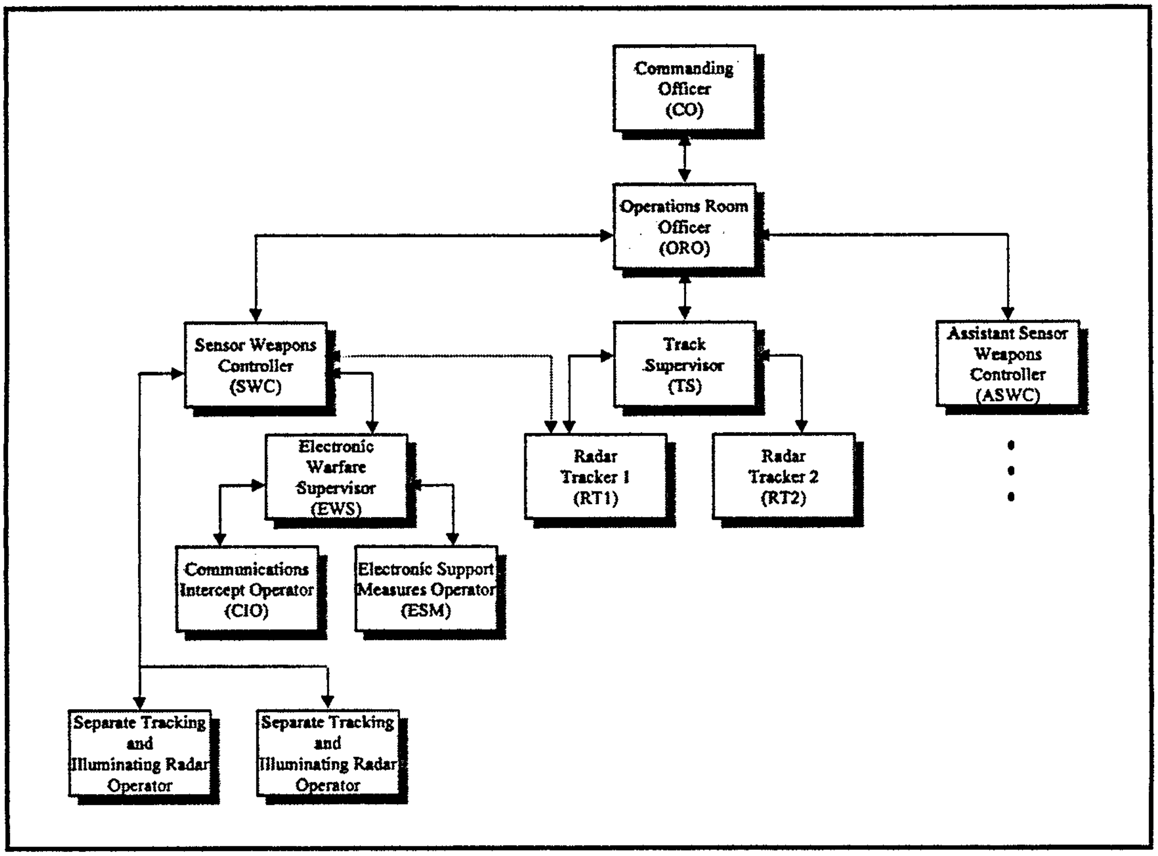

FIGURE 5 - Combat System Operator Organization

The CO is responsible in all respects, but normally delegates control and charge of the ship to personnel of his/her choice, usually the Operations Room Officer (ORO), to allow the most efficient deployment of the ship. In reality, however, decision-making performance is the result of a coordinated team effort and communication among its members is critical in sharing information relevant to the mission and the decision-making tasks involved. Various means of communication are provided to enable this. For example, team members monitor information disseminated to and from other units at

sea and ashore, communicate with each other and provide feedback, when required, by means of headphones, using several channels with left and right ears listening simultaneously to different circuits. In addition, display boards within the Operations Room are used to promulgate current information on perceived threats and assist in activating pre-planned responses to highly time-stressed events such as the sudden detection of an ASM flying toward the ship.

Collectively, the various functions of the operators in conducting the AWW involve a number of perceptual and cognitive processing activities and behaviours. For example, framed with respect to the time line from "birth" to "death" of a single air or surface contact of interest, these activities span the moments from first detection of the contact (perception), its investigation, assessment and evaluation in the context of the current mission (situation and threat assessment), development of a course of action (planning), to an engagement or course of action decision (decision making) and monitoring of the ensuing engagement if enacted against the contact (execution). This sequence of activities necessitates a highly dynamic flow of information and decision making involving a number of operators, with a concomitant requirement for developing a common, shared representation of the situation so that team members are always working synergistically toward achieving a common goal.

However, the work environment of the AWW is even more demanding than the above snapshot of activities related to treating a single contact suggests. At any given moment, numerous AWW contacts may have been detected, with each contact at its own point in its engagement activity sequence. In addition to being monitored within their individual engagement life-cycles, contacts may need to be monitored in relation to each other for additional clues to their intentions. Connections or relationships between contacts therefore need to be understood for their tactical significance to the mission.

Perceptual and cognitive processing activities of operators are further complicated by the fact that the underlying contact information is derived by continuously fusing organic and non-organic data, including intelligence information from shore and various deployed units, to build a coherent Maritime Tactical Picture (MTP) of the ship's area of interest. This can lead to processing large volumes of data under stringent time constraints. Moreover, the generally imperfect nature of the data, which can be uncertain, incomplete, imprecise, inconsistent, and ambiguous, or some combination of these, means that at any given moment the MTP is only an approximation to the true state of affairs and that there may be several likely interpretations of the tactical situation. At present, in the CPF, these various fusion tasks are manually performed by operators, communicating among themselves to achieve a shared understanding of the situation.

All of this calls for operators to work together effectively as a team in a highly coordinated manner toward common objectives. Their various task activities involve:

- continuously scanning consoles and monitoring the communication nets for significant events and alerts;

- exchanging information among themselves or passing information up the chain of command;

- issuing or responding to orders depending on an operator's position and role in the chain of command; and

- focusing attention at any given moment among several competing stimuli and dividing attention between several competing or complementary multiple tasks in response to operator-specific goals.

In fact, so much needs to be done at any given time that careful attention and time management at both the individual and team levels are critical for effective performance. It is evident from this discussion that in

the highly dynamic environment of the AWW critical incidents happen at indeterminate times as events unfold in time, resulting in dynamically shifting, multiple goals to be achieved and numerous perceptual and cognitive tasks to be performed by various operators at various times toward cooperatively accomplishing these goals.

In summary, effective decision making in this high stakes environment requires perceiving and understanding the tactical situation confronting the ship sufficiently well to allow intelligent and timely selection of courses of action in response to perceived threats to the mission. This involves accessing large amounts of a priori information and dynamically updated information, including doctrine, tactics and intelligence information and real-time contact information, and developing a shared understanding of this information, as necessary, to support a coordinated team effort. This results in a complex, dynamic, real-time, data- and goal-driven multi-tasking environment for the Operations Room team. Goals are continuously created, prioritised and steps taken toward their achievement with continuous attentional shifts between goals dictated by their time-dependent relative priorities. It is therefore vital that human and machine resources are effectively managed. This real-time resource management problem is particularly severe when concurrent goal satisfaction under critical time constraints requires careful scheduling of shared resources that are essential for the achievement of these goals.

The above discussion has described the complexity of the AWW environment in terms of the cognitive demands this environment imposes on the operators who must interact with it. This is consistent with the literature on cognitive systems engineering. For example, Woods (Refs. 11-12) states that there are four dimensions that define the cognitive demands of a work domain: dynamism, the number of its parts and the extensiveness of interconnections between those parts, uncertainty, and risk. In view of our description of the AWW domain, it is evident that this decision-making environment rates as a highly cognitively demanding domain. In practice, its complexity for the decision maker can be expected to vary, depending on the

nature of the conflict involved, which may span the spectrum from traditional saturated, open-ocean scenarios to scenarios with highly uncertain elements, as in combined littoral operations where there may be many kinds of platforms of many nationalities with the potential for interactions with neutral parties becoming embedded within the engagement.

The AWW environment is also a good example of what has recently come to be described as a naturalistic decision setting (Ref. 13). Such settings are characterised by a number of important situational factors, such as ill-structured problems, uncertain, dynamic environments, conflicting, shifting, or ill-defined goals, many action-feedback loops, time constraints, high stakes and pressures, multiple decision makers, and organizational goals and norms. In general, some or all of these factors may be present to some degree in a given naturalistic domain (Ref. 13). An important implication is that naturalistic environments tend to be complex environments for human decision makers.

In view of these considerations, aiding the decision maker in the environment of ship-based AWW stands to benefit greatly from research in the various cognitive technology communities (cognitive systems engineering, human factors, cognitive psychology, ecological psychology, etc.) aimed at understanding how real decision makers cope in cognitively demanding environments and, more importantly, at using such knowledge in the design of user-centred systems that provide tools to expand human abilities to perform effectively in the face of complexity (Refs. 7, 9-17). These issues are touched on in the remaining sections of this chapter.

3.2 Descriptive Models of Tactical Decision Making

Our focus here is on descriptive models of tactical decision making that appear to hold potential for guiding MSDF/STA/RM system design in the AWW. This is ongoing work at DREV and its conclusions are therefore only tentative for now. The reader interested in situating decision making in the wider context of the C2 process can consult Ref. 18 for an overview of

several competing conceptualizations of this process, including the SHOR (Ref. 19), OODA (Ref. 20), MORS (Ref. 21) and M/A-Com models (Ref. 22) and the Lawson C2 cycle (Ref. 23).

Decision making is a critical function performed by combat system operators in the AWW. Designing an MSDF/STA/RM DSS that offers effective aids for this function requires a detailed understanding of the various decision processes that arise in the AWW and the ways in which human decision-making capabilities can be supplemented or aided, depending on the mode of interaction between the human and the automated system, without forcing operators to adopt procedures and strategies that might in the end degrade performance.

To this end, an important consideration for system design is the development of descriptive models of the various decision processes in the Operations Room. The importance of these models is that they they permit integrating knowledge of operator decision behaviour into the design. They assist in structuring requirements on the joint human-machine system and in describing the activities and processes underlying human-machine interactions, as an integral part of a principled approach to allocating tasks between the human and the automated system.

It is important to note that instantiating decision-process models for system design needs to be done within some general framework for interpreting all pertinent aspects, of an overt or covert nature, of operator behaviour. Examples of such frameworks include a cognitive task analysis (Ref. 24) and a cognitive work analysis (Ref. 25). Various knowledge elicitation strategies and knowledge representation formalisms would therefore need to be employed to capture and represent the knowledge of current operators and other subjects who are subject-matter experts (SMEs) on the various Operations Room activities. This includes knowledge of:

- the decision processes involved;

- their decision goals;
- informational cues that trigger the various decision processes and provide the information needed to make a decision;
- both individual and team-level cognitive strategies employed by operators for combining and interpreting these cues; and
- meta-cognitive strategies used to account for time pressure on making a decision, and for focusing or dividing attention between several competing or complementary decision tasks and trading off among competing goals;

and so on. Reference 26 provides a compilation of current knowledge elicitation techniques that may be used to acquire such knowledge.

The discussion here gives a brief presentation of a preliminary synthesis of some recently developed descriptive models of human decision making in naturalistic environments. The reader can consult Ref. 13 for a review of many of the naturalistic models of decision making which were consulted to arrive at this synthesis. Naturalistic decision models aim to describe how human decision makers actually make decisions in complex, real-world settings. Consistent with the joint human-machine perspective of cognitive systems engineering (Ref. 11), adopting a descriptive approach assumes that if we are to provide meaningful decision support in an application domain, it is vital to understand the decision-making strategies employed by its real decision makers. A decision-making strategy refers to a well-defined way the decision maker uses to make a non-obvious decision in a situation where there are several potential alternatives. Decision alternatives need not be explicitly articulated, but there must be at least an implicit acceptance by the decision maker that more than one course of action is indeed feasible.

The naturalistic approach emphasises the point "that phenomena observed in complex natural environments may differ substantially from

those observed in the laboratory based on decontextualised tasks performed by novices with little stake in the outcomes" (Ref. 13). In fact, much of the more traditional, analytically-based decision making research that appears in the literature has been criticised on this very point, viz., these efforts study human subjects operating in artificially created laboratory settings using normative models to prescribe rational decision-making behaviour on reasonably static tasks. This certainly raises the possibility of the limited representativeness and generalizability of the results of the latter research to the AWW environment.

The synthesis does not postulate a single ideal model of human decision making. Nor does it attempt to supplant traditional analytical models of decision making (e.g., decision trees, Bayesian networks) that would tend to be embraced exclusively in a purely decision analytic approach. Rather, a balanced perspective is adopted, whose aim is to achieve an integration of models by identifying the appropriate contributions of the various models for supporting decision making in the AWW.

More specifically, the framework for model synthesis suggests that decision making needs to be viewed with respect to a cognitive continuum. Recognitional/intuitive/satisficing decision-making models are at one end of the spectrum. In such models, the decision follows almost immediately from recognizing the type of situation involved and recalling what actions have typically worked well in the past. Decision-making models at the other end involve explicitly identifying and comparing feasible courses of action and choosing the optimal solution. These models are analytical/optimizing-based decision-making models. In terms of cognitive demands imposed on the decision maker in unaided decision making, the former models are less cognitively demanding than the latter. Evidently the value and importance of this spectrum of models for decision making in the AWW needs to be established. Interestingly, a recent study of the decision requirements for anti-air warfare (AAW) officers in the Combat Information Centre (CIC) of an AEGIS cruiser found a heavy reliance on recognitional strategies of decision making (Ref. 27). It should not be surprising, therefore, that if

analytical/optimizing models are to have any value in a setting like the highly time-constrained environment of the AWW, there is a clear need for providing high-performance tools that can reduce their cognitive demands and support the decision maker in their effective use.

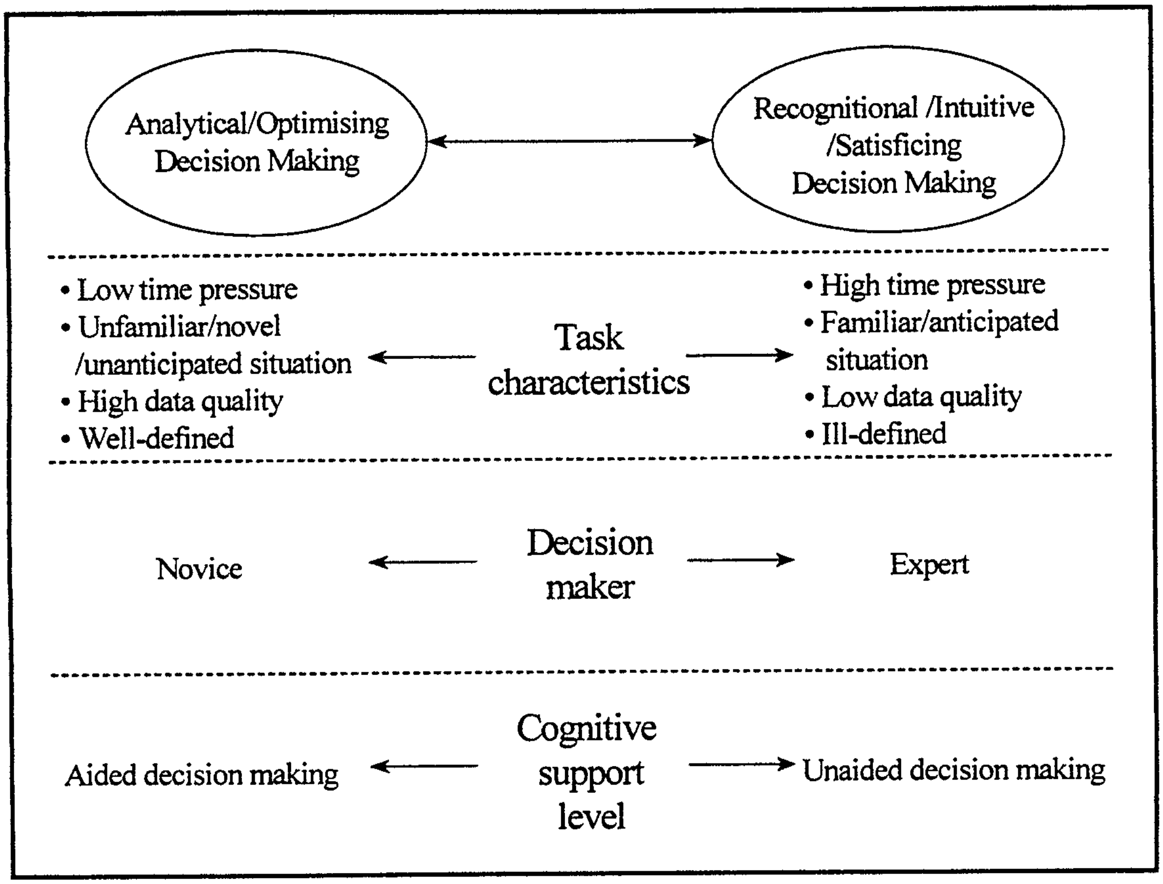

FIGURE 6 - Decision-making continuum

Placing a specific decision-making situation on the continuum is multi-dimensional. We highlight three of its dimensions here. The first two dimensions relate to the characteristics of the decision task, including the environmental constraints under which the task is to be performed, and the knowledge and experience of the decision maker that is relevant to the task. Recent work in naturalistic decision making has concentrated on unaided decision making. However, to be useful in a support setting, as is the aim of the MSDF/STA/RM DSS, decision making must also reflect the ecological

impact of the level of cognitive support available and used by decision makers. For this reason, we have added this feature as another dimension to be considered. The decision-making continuum is shown in Fig. 6, along with the three aforementioned dimensions for placement of a decision process on the model continuum. This figure suggests that movement to the right on any of the dimensions shown induces a general shift toward the recognitional/intuitive decision making end of the spectrum, while a move to the left induces a corresponding shift toward analytical decision-making models.

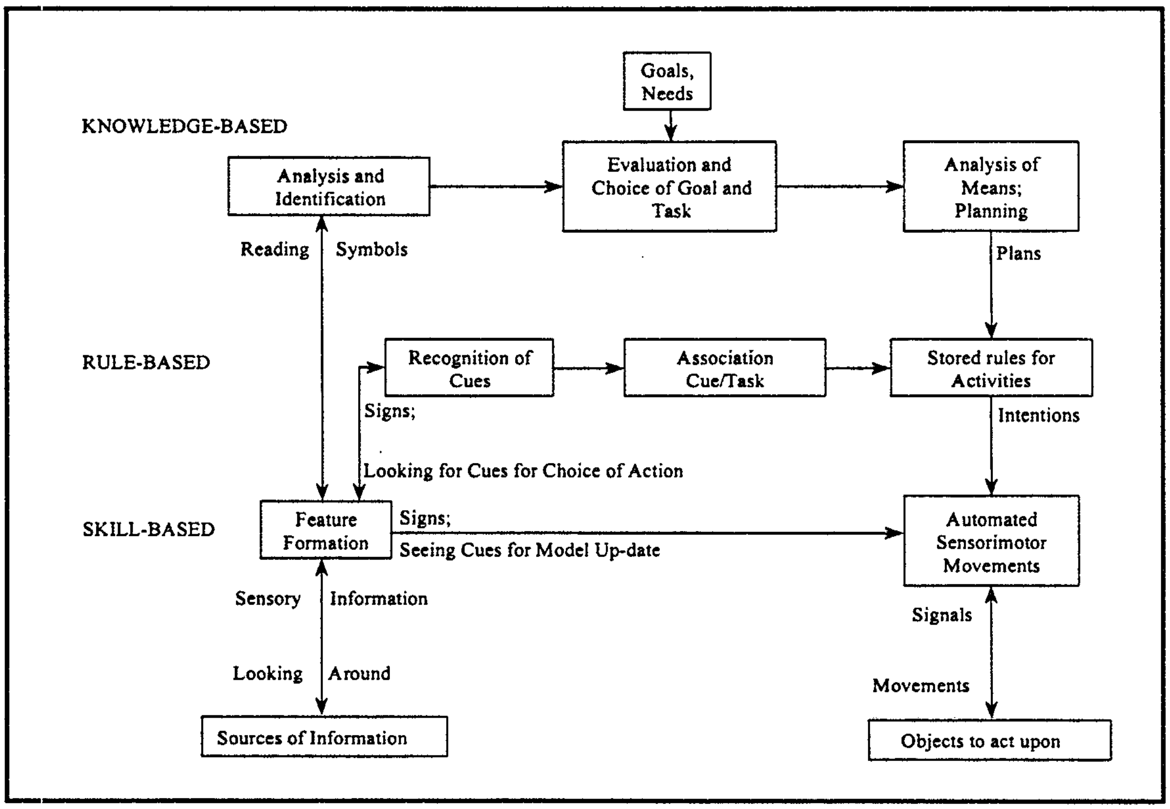

FIGURE 7 - Rasmussen's skills, rules, knowledge framework

Adopting a spectrum of decision-making models is consistent with a number of previous research efforts. For example, Hammond and his colleagues (Refs. 28-29) have developed a theory of task characteristics that tend to induce different types of cognitive activity (analytical, quasi-rational,

and intuitive) on subjects and have described how human performance can vary as a function of the correspondence between task properties and the type of cognitive activity in which subjects engage while performing the task.

Distinguishing between levels of cognitive activity is also an important aspect of Rasmussen's skills, rules, knowledge framework applied to decision making (Refs. 25 and 17). These various levels are shown in Fig. 7. The theory suggests that decision-making behaviour depends on the level of expertise of the operator and the degree of novelty of the situation confronting the decision maker or his/her unfamiliarity with it. At the skill-based level, people engage in fluid perceptual-motor control; at the rule-based level, the decision situation is recognised allowing decision rules to be implemented based on previous experience; finally, at the knowledge-based (also referred to as model-based) level, rational, knowledge-based or analytical problem solving methods are employed by novices or by experts facing unfamiliar or unanticipated situations.

An important descriptive model of naturalistic decision making that is located at the recognitional end of the decision-making spectrum is Klein's model (Refs. 13, 15 and 17). His model, derived from studying various naturalistic decision settings, including experienced urban Fire Ground Commanders, Tank Platoon Leaders and Wildland Fire Incident Commanders making decisions under conditions of high time pressure, is shown in Fig. 8. The model suggests that in such situations decision makers match the immediate problem situation to a condition in memory and retrieve a stored solution which is then evaluated for adequacy. If it passes, it is adopted; otherwise, it is either modified or another solution is retrieved and evaluated. This leads, therefore, to a serial evaluation strategy, based on mentally simulating the effects of one option at a time to establish its adequacy or identify its likely problems.

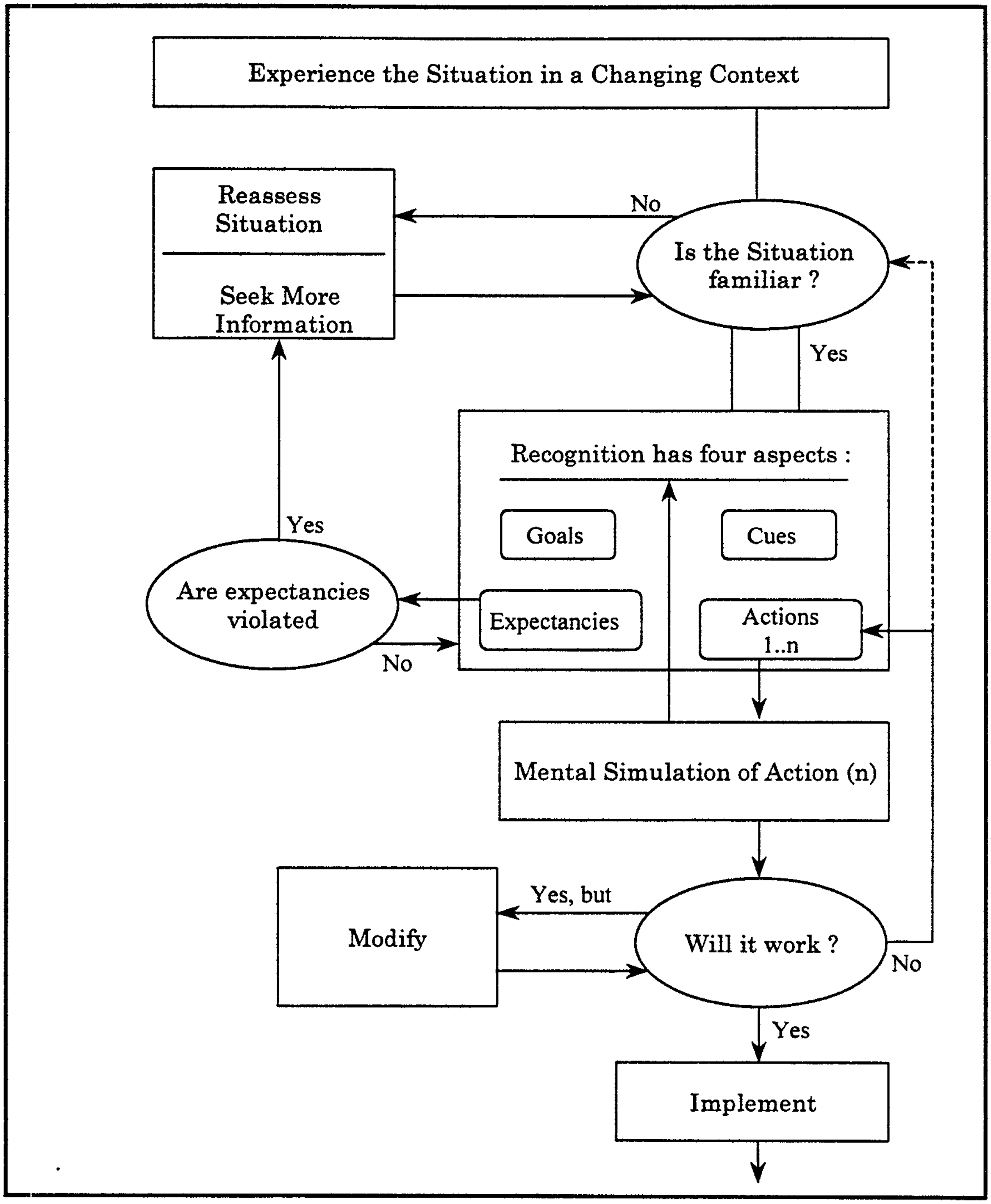

FIGURE 8 - Klein's recognition-primed decision model

Klein's model also provides features for explaining dynamic goal selection, attention to critical cues, expectancies regarding future states of the situation, and the link between situation recognition and understanding and course of action selection. Including expectancies in situation recognition permits being prepared in case surprises arise, which indicates that the situation has not been correctly recognised.

To close this section, we highlight some general characteristics of decision making which manifest themselves in some form in all the various decision making models. Human decision making is a cognitive process that is triggered in any specific situation by an initial perception of an occurrence in the environment (a cue) that signals a need or opportunity for a decision. Once triggered, decision making involves two cognitive components: situation assessment and selection of a course of action or a response. Once the commitment to a response is made, it is implemented, usually accompanied by monitoring the implementation and feedback from the environment.

Situation assessment, the first cognitive component of decision making, is an uncertainty reduction process involving judgments needed to extract pertinent information from the uncertain environment. The nature of the situation is interpreted based on the various environmental cues that are perceived. A number of components of the situation assessment process are possible, including, continuous attention to and monitoring of environmental cues, diagnosing and interpreting the significance of the cues in light of current goals, assessing whether information is adequate for making an interpretation and seeking further information, as may be needed in uncertain situations where there are insufficient, ambiguous, vague, conflicting or contextually uninterpretable cues, and assessing the level of risk and time pressure present in the situation. The human's situation assessment process is the active process by which he/she achieves situation awareness (the state). Situation awareness (SA) can be thought of as the human's time-dependent mental model of the state of the environment (the human's situation model). Endsley has provided a more specific definition of

situation awareness which, she suggests, is applicable across different task domains:

> "Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Ref. 30).

Endsley places the various phases and components of situation awareness on a hierarchy as indicated in Fig.9.

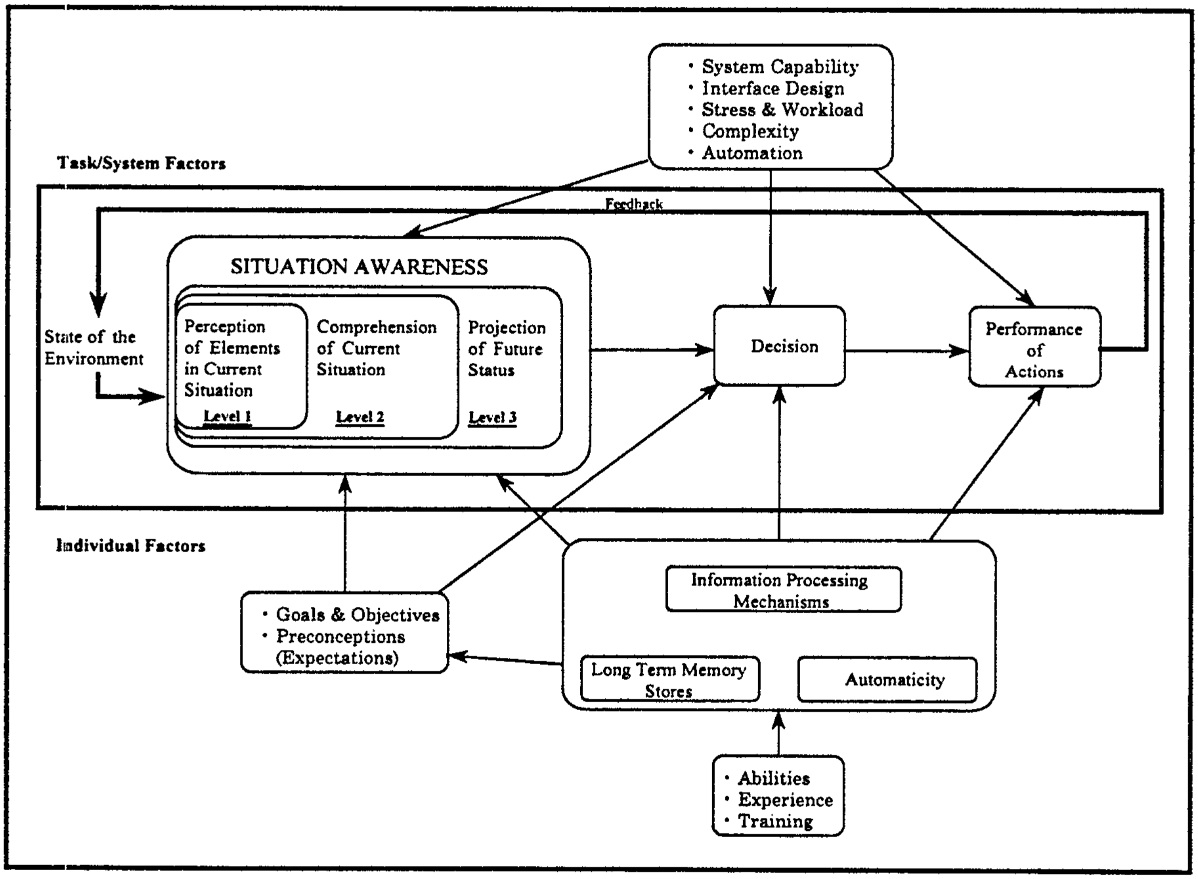

FIGURE 9 - Endsley's model of situation awareness in dynamic decision making

The model shown there also draws attention to the variety of task/system

factors and individual factors that impact situation awareness and decision making. We examine some of these issues further in Sections 3.3 and 3.5.

Selection of a course of action or a response, the second cognitive component of decision making, extracts a course of action from the judgments derived by situation assessment. This involves recognizing the response requirements posed by the situation, identifying options, evaluating their merits in the context of the assessed situation, taking account of the constraints imposed by the situation, and deciding on a response.

3.3 Decision-Making Performance

It is evident from our discussion in Section 3.1 that combat system operators in the ship's Operations Room work in an environment that is highly demanding on their perceptual and cognitive capabilities. In highly dynamic situations with a large number of contacts to be processed, handling the large amounts of data could quickly overwhelm human capabilities. Moreover, it should hardly be surprising that there is high potential for inadequate and even degraded human performance due to the numerous stressors of a very hostile environment. This raises the question: What are the human performance limitations that need to be supported by automated tools which we would consider being part of an integrated MSDF/STA/RM DSS? Potential answers are provided by work in the U.S. Navy's Tactical Decision Making Under Stress (TADMUS) program (Refs. 31-33). This program "is being conducted to apply recent developments in decision theory and human-system interaction technology to the design of a decision support system for enhancing tactical decision making under the highly complex conditions involved in anti-air warfare scenarios" (Ref. 33).

Data in the TADMUS program compiled from experiments with a number of tactical teams using a six-station testbed environment (DEFTT - Decision Making Evaluation Facility for Tactical Teams) that simulates computer workstations in the CIC of an AEGIS cruiser has revealed a number of categories of tactically significant errors that can arise, leading to

a failure to take appropriate actions. Most of these error types have been identified as candidates for requiring good decision support (Ref. 31). This list is given below, where in brackets alongside each error category are given, when possible, the primary system component(s) that would be envisioned to provide the required support in an MSDF/STA/RM DSS:

- slow to detect and respond to contacts of interest (MSDF, STA, RM);
- communications within team not acted upon;
- delay in taking contact of interest under close control (STA, RM);
- delay in issuing standard warnings (RM);
- premature issuing of warnings (RM);
- failure to report to the officer in tactical command (STA, RM);
- lost tactical picture (MSDF, STA);
- failure to use reported sensor information (MSDF, STA);
- failure to clear clutter (MSDF, STA);
- failure to verify reported track;
- failure to take appropriate response (RM);
- failure to use softkill (RM);
- issue of wrong warning level (STA, RM); and
- failure to acknowledge or act upon intelligence reports (STA).

Reference 31 suggests that two error types shown above (communications within team not acted upon and failure to verify a reported track) are best addressed through training of operators for automaticity since these errors are of a procedural nature.

Finally, we note that approaches to enhancing decision-making performance in the Operations Room can be viewed from at least two complementary perspectives, both of which will need to be considered as part of the process of designing an MSDF/STA/RM support system. It involves the distinction that needs to be made between human competence and performance (Refs. 34-35).

In the case of the Operations Room team, competence refers to the underlying individual and combined knowledge level and capability for producing a behaviour or for processing information that is a prerequisite for effective performance. On the other hand, performance is the behaviour operators empirically exhibit as they execute their tasks in a real scenario. The mapping from underlying competence capabilities and knowledge to performance behaviours is done by the human's information processing mechanism. This is illustrated in Fig. 10. Human information processing (Ref. 35) is subject, however, to a number of clear limitations and deficiencies, such as finite cycle time, limited working memory, limited ability to perceive and process information and cognitive biases (see, for example, Ref. 37). It is also negatively impacted by environmental factors or stressors and almost random errors or slips. This discussion suggests that support tools for enhancing performance will need to provide support at least in the following two complementary areas:

- enhancement of the fundamental competence of its users; and
- support for their information processing limitations and deficiencies.

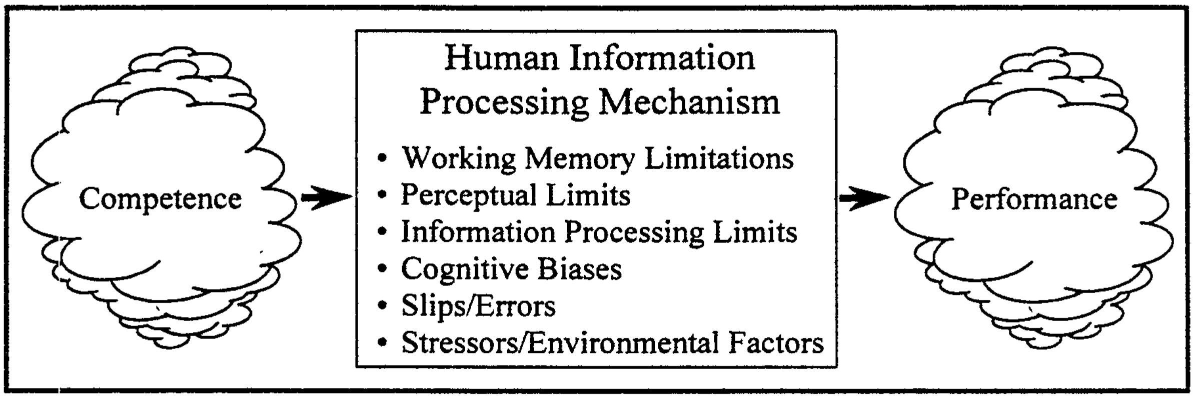

FIGURE 10 - Competence, Human Information Processing Mechanism, and Performance

The first type of support is aimed at bridging the gap between the novice and the expert operator, as well as enhancing the competence of both the individual and the team, be they novice or expert in their tasks. The second type aims to compensate for degraded or limited human performance at both the individual and team levels, particularly in highly stressing and dynamic situations.

3.4 Framework for an Embedded Decision Support System

The research described in this report is aimed at exploring concepts for the development of a real-time decision support system, an MSDF/STA/RM system, that interacts with combat system operators to support the tactical decision making and action execution processes in the ship's Operations Room. More specifically, with respect to the various decision-making processes involving individual and/or team members, the roles of the various sub-system components are:

- MSDF will provide a capability for supporting perception by developing a tactical picture of the AWW derived by fusing all available data;
- STA will provide a capability for enhancing situation awareness by supporting the interpretation of the tactical picture and the development of a common, shared mental model, as required by team members; and

- RM will provide a capability for enhancing decision making and action execution by assisting in the formulation and selection of a course of action that appropriately responds to the situation and by coordinating and directing action implementation once a decision to act has been made and an action is being executed.

In the current conception, the MSDF/STA/RM system is an embedded component of the ship's CCS. This is shown from a high level perspective in Fig. 11.

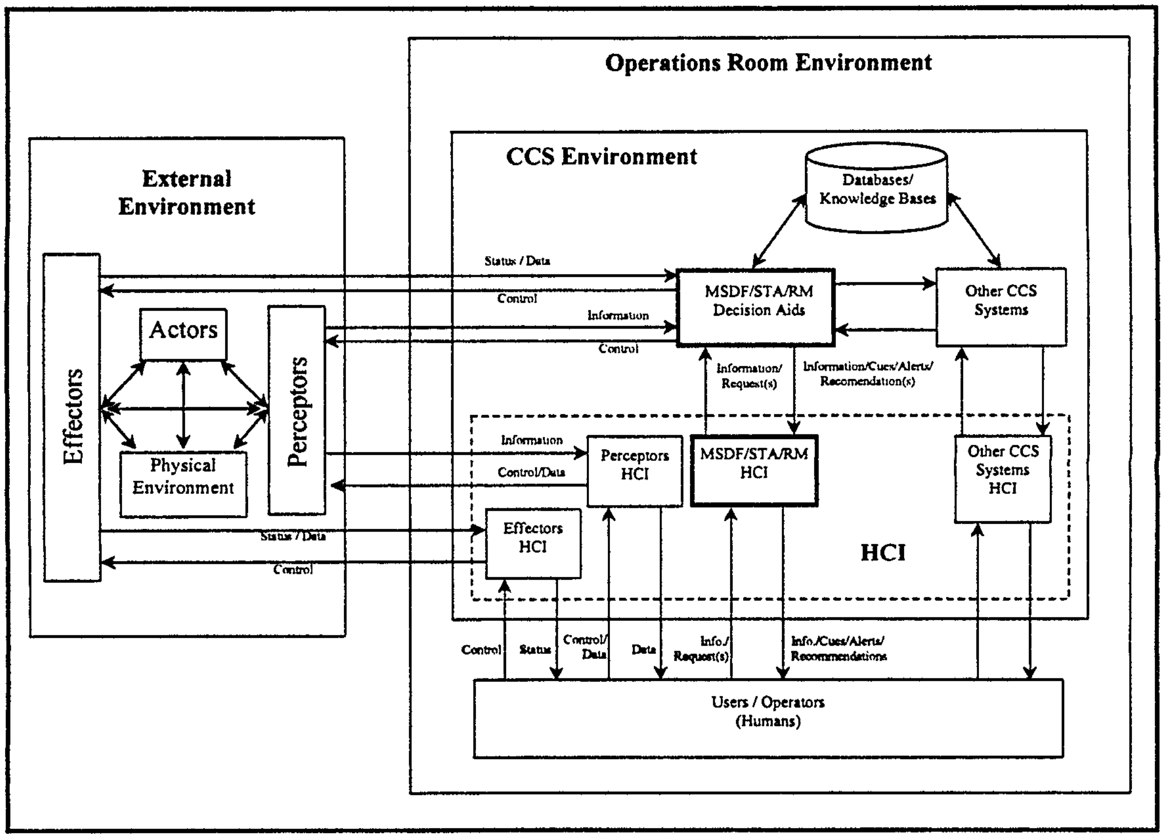

FIGURE 11 - MSDF/STA/RM integration framework

The environment shown there is decomposed into the portion that is within the ship's Operations Room and the portion outside, including the perceptors (organic and non-organic information sources), effectors (active and passive weapon systems), the actors (threats, friends, neutrals) and the physical

environment external to the ship. The automated system environment is everything in the CCS of a hardware or software nature, including the various HCIs, databases/knowledge bases and other CCS systems. These databases/knowledge bases contain a variety of a priori knowledge, including doctrine, and strategic, EW and intelligence information.

3.5 Automation Issues

In the previous sections of this chapter, we touched on a number of cognitive issues that need to be considered within the design space of the DSS. There are still other issues that need to be explored. In fact, as previously observed, a comprehensive study of systems engineering issues that examines technological and cognitive issues jointly remains to be undertaken. This includes conducting knowledge acquisition sessions aimed at modelling human expertise, competence and performance, and using this knowledge to do a functional allocation between the Operations Room team and the automated system and defining a model of cooperation between these two joint-system components.

Developing an appropriate automation philosophy is therefore a very important part of the system design process. Traditional automation philosophy is to automate as much as possible, which leaves humans playing a monitoring role, one for which they are not well suited. Endsley (Ref. 38) has raised the out-of-the-loop performance problem as a major potential consequence of such an automation philosophy since it leaves operators of automated systems handicapped in their ability to take over in the event of automation failure.

Two approaches to task allocation are adaptive automation and providing a variety of operator-system modes of control. Adaptive automation involves an adaptive task allocation between the human and computer (Refs. 39-40) depending, for example, on which party has at the moment more resources or is the more appropriate for performing the task. A

potential problem, however, is that it requires operators to keep up with who is doing what as the allocation changes.

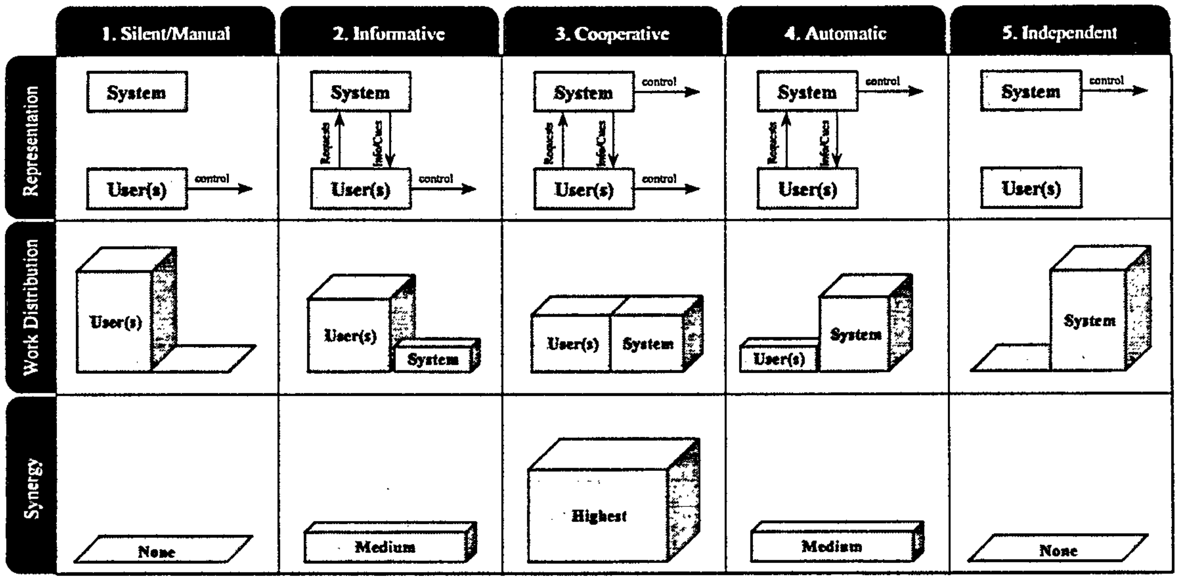

FIGURE 12 - Operator-System modes of operation

The approach of providing various levels of operator-system control, which is in fact similar to that currently implemented in the CPF, is illustrated in Fig. 12, where representations of five operator-system *modes of* operation are shown, along with the variation in levels of work distribution and synergy between the automated system and the operator implied by these various levels.

The silent/manual mode is characterised by the fact that the operator has all the authority for deciding and initiating action. The system is completely passive and provides no help or assistance whatsoever to the operator. In informative mode, the system only provides the operator with support information; however, all decisions and actions are performed by the operator. In cooperative mode, both the system and the operator make decisions and effect actions in a collaborative manner. There is maximum synergy between the system and the operator. The operator is presented with alternatives and solutions who then interacts with the system to make a decision and initiate action. In automatic mode, the system makes all

decisions and initiates actions but the operator is allowed to veto a decision or the implementation of an action. The system can operate in complete autonomy. The independent mode completely excludes the operator from the decision process. All decisions and actions are performed by the system and the operator is locked out. In this mode, the system operates as a black box without any required operator interface. The division of roles between the system and the operator in the various modes is summarised in Table I.

TABLE I

Operator-System roles in the various modes of operation

Mode	Operator's role	System's role
1. Silent/Manual	Decide & Act	Passive
2. Informative	Decide & Act	Support
3. Cooperative	Select and Concur	Decide, Act only if operator(s) selects or concurs
4. Automatic	Veto	Decide, Act automatically unless operator vetoes
5. Independent	Passive	Decide & Act

Naturally, it is also possible to adopt a hybrid approach, between the two extremes, depending on the specific decision-making process involved. For example, under specific pre-approved conditions on the context, determined by an operator, the system could make a decision and implement the appropriate actions on his/her behalf; alternatively, this type of mixed-initiative human-computer behaviour could be implemented in a ship's associate system with an intelligent, adaptive HCI that can take the initiative in identifying and deciding how to satisfy the needs of operators based on some embedded operator model.

In closing this chapter, we note that a fundamental problem in the design of a major decision support capability like an MSDF/STA/RM support

system is how to design the system so that operators will trust it and therefore use it appropriately. Muir (Ref. 41) makes a number of recommendations about the calibration of trust by humans in machines that may be useful to consider here. They include:

- improving the operator's ability to perceive a decision aid's trustworthiness;
- modifying the operator's criterion of trustworthiness;
- enhancing the operator's ability to allocate functions in a system; and
- identifying and selectively recalibrating the operator on the dimension(s) of trust which is (are) poorly calibrated.

She also provides several recommendations of various means for accomplishing these goals.

4.0 OVERVIEW OF THE SRTE PROJECT

Previous MSDF, STA and RM R&D activities by DREV researchers have approached the problem of satisfying perceived future shipboard CCS data and information processing requirements in an essentially discrete, bottom-up manner. MSDF has focused on analysing, developing and evaluating advanced techniques to automatically produce the optimal estimate of the position, kinematic behaviour, and identification of all objects surrounding a single ship, mainly through the fusion of data from dissimilar organic sensors, while including non-organic information. STA has been concerned with providing reliable assessments of the situation in which the ship is operating that are important for the successful accomplishment of the mission. Finally, RM has aimed at providing planning and decision support functionality in the CCS to aid military personnel in the integrated use of critical resources and to manage their coordination in accordance with such decisions. The decision making referred to here relates to refining and enhancing perception (i.e., sensor management) as well as the management of the ship's weapon systems.

This previous research has provided certain pieces of the puzzle, while some other pieces still need to be added to complete the picture. Missing pieces represent some MSDF/STA/RM techniques/methods which are not yet fully understood for implementation on the CPF, or techniques/methods that are understood, but their real-time implementations have not yet been proven. Moreover, these studies have been performed as a number of separate projects and a complete CCS with embedded MSDF, STA and RM techniques and methods operating in real time cannot yet be demonstrated.

Despite the apparent compartmentalization of previous R&D efforts, where the focus of individual efforts has been largely shielded from each other, it is clear that in future shipboard CCSs the various MSDF, STA and RM processes will need to work together in an integrated, synergistic manner, to support the situation awareness and decision requirements of

combat system operators and improve operational effectiveness in the ship's Operations Room. Therefore, while MSDF outputs low level perceptions of the tactical picture, STA uses these to support the development of higher-level abstractions needed to interpret their meaning and tactical significance. The principal observe-orient-decide-act (OODA - Ref. 20) C2 loop is then closed via RM, thereby providing effective response in support of the mission to significant events in the external, hostile battle environment.

In parallel with continuing efforts within the DFRM group to effect refinements and improvements of individual processes, the SRTE project has been initiated that establishes an important new research focus, aimed at addressing this integration problem in a top-down manner and at evaluating its potential solutions. The project will concentrate its efforts on the Above Water Warfare.

At a high level, it is known that integration requires the optimal use in real time of available organic and non-organic information to build a coherent tactical picture to support human or automated decision making and to provide effective response coordination. However, the specifics of this integration have yet to be determined. For example, only the principal OODA loop was mentioned above, but many sub-loops involving information flows at different velocities, with the man in the loop at a variety of levels and in varying roles, are in fact involved. Moreover, both for the sake of the performance of the individual processes and the overall performance of the integrated system, there is the important requirement to specify the temporal dimensions of the system's behaviours. Integration has to be achieved in an environment in which response times are at a premium and the necessity for a variety of synchronised interactions at various points of these loops with the combat environment will require critical timing constraints on system behaviour to be satisfied. In addition, it is likely that such integration may require vastly greater computing capabilities than is present in the current generation of naval surface combatants if satisfactory, predictable and robust real-time behaviour of the integrated system is to be achieved. Questions of identifying how much additional computational

capability is required and where, as well as the benefits to the CCS to be derived from such increased capability, are important issues that need to be addressed.

The objectives of this project could be accomplished by performing a number of small and separate R&D activities (as was done in previous studies) whose results would then be integrated into an enhanced CCS. However, by following this approach, the top-down methodology necessary for evaluating the many tradeoffs arising in the development of an integrated real-time MSDF/STA/RM system cannot be accomplished. Furthermore, each separate task would have to build its own expertise and framework, before actually performing the research, increasing the cost of the overall program in the redundant, overlapping activities for each task. For these reasons, a large-scale project where real-time issues for an integrated MSDF/STA/RM system for the CPF are studied in a coordinated manner has been selected.

The high-level aim of this project is to capture and analyse the real-time requirements of a CPF CCS integrating MSDF, STA and RM into a system using all information available on the current (and to some extent the future or upgraded) ship. This project will consolidate DREV's existing expertise, framework and proof-of-concept software and define how the CPF's combat system performance may be optimised through the use of numeric and AI techniques for an integrated real-time MSDF/STA/RM system in the heart of its CCS.

An important aspect undergoing pioneering development within the SRTE project is the development of a capability for evaluating the performance and capturing the requirements of a complex, distributed real-time system like an MSDF/STA/RM system. This involves the design and implementation of an environment, called the Simulated Real-Time Environment (SRTE), for evaluating concepts, algorithms and architectures for MSDF/STA/RM. In this highly novel approach, all real-time system development and experimentation is conducted on a simulator running on a host architecture whose purpose is to capture the functional requirements,

temporal behaviour and real-time performance of the MSDF/STA/RM integration.

The simulation engine in the proposed environment will simulate the real-time execution of the automated components of the MSDF/STA/RM system running on a user configured target hardware architecture. The target could be a single parallel machine or a collection of (heterogeneous) machines connected via a local area network (LAN). The simulator will accurately simulate the timing behaviour of system code running on the processors of the target. At the same time, it will correctly interleave events associated with communication between threads running on the same processor (machine) or different processors (machines), as well as events that arise from interactions between MSDF/STA/RM and the external battle world in which it is operating. Both open-loop and closed-loop analyses of system behaviour will be achievable. This environment will permit debugging, testing and non-intrusive performance monitoring of MSDF/STA/RM code.

The level of detail that will be available in SRTE permits an unprecedented ability not just to uncover situations in which automated system performance breaks down, but also to reveal exact causes, and - because the simulation maintains a complete picture of system events - to suggest remedial action. Moreover, since the automated system is only being simulated, fixes to problems can be attempted immediately, and their success and side-effects evaluated speedily.

The immediate focus of the project is the CPF platform, as a means of enhancing DREV's capability to provide consulting services concerning envisioned functionality and performance enhancements to the CCS in data fusion, and information evaluation and resource management decision aiding, as part of the mid-life upgrade of the CPF expected in the FELEX program. However, it is also likely that the concepts, techniques and algorithms to be developed in the SRTE project could apply to the improvement of the CCS of a TRUMP platform or for determining CCS

requirements for the expected replacement of this class of ship in the next century.

Since an important purpose of this project is to support risk mitigation in the design of the next generation of the CPF's CCS, an initial step in exploring MSDF, STA and RM concepts in this project will concern the development of a baseline MSDF/STA/RM system. The objective is to develop an integrated real-time system that would provide an enhanced CCS for the CPF, with an improved target surveillance and tracking capability and an improved Threat Evaluation and Weapon Assignment (TEWA) capability. Then, in a later phase, these concepts will be refined and extended (e.g., more sophisticated sensor fusion techniques, a more complete situation assessment capability, the inclusion of softkill weapons in the resource management model, etc.) in order to investigate some multiple platforms issues.

To meet these objectives, the project is being undertaken as a set of four activities:

Activity I	Methodology for Specification and Design of a Generic Real-Time MSDF/STA/RM System and Integration Framework
Activity II	Development of a Simulated Real-Time Environment (SRTE)
Activity III	Capture of Real-Time Requirements for a Baseline MSDF/STA/RM System
Activity IV	MSDF/STA/RM Refinements and Extensions to Multiple Platforms

Each activity is divided into tasks and sub-tasks. The technical details of these four activities, including their various tasks and sub-tasks, are described in Chapters 5.0 to 8.0.

5.0 ACTIVITY I: METHODOLOGY FOR SPECIFICATION AND DESIGN OF A GENERIC REAL-TIME MSDF/STA/RM SYSTEM AND INTEGRATION FRAMEWORK

This activity is pivotal to the SRTE project as it deals with establishing a concrete, systematic approach to exploring and managing the complex real-time system design issues and tasks involved, as well as with a number of related matters. Inevitably, the successful development of a real-time system of the size and complexity of an MSDF/STA/RM system requires a well-defined methodology for specification and design of its sub-systems to be followed, and the adoption of a basic framework for achieving their integration. An ad-hoc, informal approach to these problems would undoubtedly lead to an inefficient use of DREV's limited human and financial resources. Of fundamental importance also is that only a small number of design alternatives would be researched and explored in this manner. What is needed is a structured, flexible and evolutionary system-level approach, as a means of establishing a foundation for exploratory real-time system design. This approach must be compatible with a general life cycle model that recognises the importance of requirements-driven top-down system design with a development process that is of an iterative and concurrent nature.

5.1 Real-Time Specification and Design Methodology

There is a large open literature dealing with methodologies and theoretical tools for specification and design of real-time systems (see, for example, Refs. 42-44). One method of classifying the various specification techniques may be based on the degree of formality used. Purely formal or assertional techniques are implicit. They are based on mathematics and are generally only useful for specifying the "what" of the system. Informal or operational techniques, on the other hand, are explicit and intrinsically executable. They use natural languages and are useful for specifying the "how". Dual techniques attempt to obtain the advantages of both approaches by their integration. In view of the strong research orientation and

exploratory focus of this project, and the expected size and complexity of a real shipboard MSDF/STA/RM system, a bias toward an operational specification methodology with good visual expressiveness for capturing and representing complex system models at multiple levels of abstraction and from multiple functional and non-functional views is highly desirable. In addition, a multi-level and hierarchical modeling approach to real-time system design, where possible, is required as a means of maintaining freedom of choices for later stages of design, and of reducing complexity and promoting modularity, reusability and extensibility of designs.

This task will consider the variety of different existing approaches and methodologies for real-time system specification and design and describe a specific methodology that is suitable for this project. An acceptable methodology synthesises many different real-time system views, uses a number of different methods and consists of an orderly series of steps to ensure that all aspects of system specification and design are considered in a disciplined and cost-effective manner. The methodology must be sufficiently expressive to describe at least the following five complementary system views: environment, function, concurrency and dynamic behavioural control, performance and system architecture. The system architecture view addresses the hardware-software co-design of an MSDF/STA/RM system as a distributed system, with code running in multiple processes on several reduced instruction set computer (RISC) processors, with interprocessor communication links between the central processing units (CPUs), taking account of hardware constraints on computation and communication bandwidth and of performance constraints such as timing. The methodology will consider all aspects of the system life cycle, including: system, hardware, and software requirements definition, environment analysis, functional analysis, behavioural analysis, performance analysis, implementation and validation. In view of the strong focus of this project on exploratory research, particular emphasis will be placed on the support provided by the methodology for iterative refinement in the various phases of work organization that deal with specification capture, exploration of design alternatives, specification refinement and software design. One feature of

this support will include the use of simulation methods for purposes of verifying or testing specifications. The use of co-simulation of hardware, software and the system environment for analysing tentative solutions to the hardware-software co-design problem will be considered in detail within the scope of Activity II.

In the case that no one single existing methodology described in the open literature can fulfill all the requirements of this project, a hybrid methodology will be developed that best meets those requirements.

5.2 Integration Framework

A framework for integrating MSDF, STA and RM sub-system components needs to satisfy a number of general requirements, including:

- compatibility with an evolutionary approach to MSDF/STA/RM system design; in particular, this means that it must be very flexible, easily amenable to prototype implementations using existing commercial off-the-shelf (COTS) hardware and software technologies, and extensible both with advances in these technologies and as DREV's R&D in MSDF, STA and RM matures; and

- modularity to facilitate independent, incremental extension of its subparts, as well as multiple implementations of these subparts both for purposes of experimenting with them and for designing and testing hybrid solutions capable of performing under a variety of functional and non-functional constraints on the system.

This task will define and specify a framework for integrating real-time MSDF, STA and RM functions in a generic integrated MSDF/STA/RM system. The use of the word generic here is to indicate that the integration framework developed will be suitable for specialization to a variety of design choices for the MSDF/STA/RM system. To do this, it will focus on features that are expected to generally structure such a system. The framework will

initially address the setting of a single ship acting in point defence operations. Extensions that are required to support area defence or wide area multi-platform operations will not be analysed until Activity IV.

Automated MSDF, STA, and RM functions will be separated into separate layers of the framework. Layering provides one means of promoting independence of system components and separating its processes along various dimensions such as the computational complexity of their processing, their nature (numeric or symbolic, reactive or deliberative, etc.) and level of abstraction, the real-time constraints on their processing, their place in the command and control hierarchy, and so on. The results of this task will produce a description of a generic MSDF/STA/RM system that includes system specifications of requirements, environment analysis, functional analysis, behavioural analysis, as well as candidate software and hardware architectures for integrating the various system functions. Descriptions of these various items are given below. The specification methodology identified or developed as a result of the work described in Section 5.1 will be followed throughout.

It is important to emphasise that the integration framework developed here will form the starting point for more detailed and specific system designs in Activities III and IV aimed at capturing and analysing the real-time requirements of a CPF, or CPF-like, CCS integrating MSDF, STA and RM functionalities into a system using all information available on the current and future or upgraded ship. Moreover, prototyping and validating these detailed designs will be conducted using the simulation environment developed in Activity II. Development and validation of real-time system prototypes running on existing (i.e., non-simulated) COTS technology is not a goal of the current project.

5.2.1 Requirements Definition

Requirements definition is aimed at defining functional and non-functional requirements of a generic MSDF/STA/RM system; the interfaces of

such a system with the external environment including sensor and actuator interfaces, the human-computer interface (HCI) and the various databases; input-output primitive data and control flows; timing requirements on recomputation rates of output flows; and input-to-output response times for all real-time transactions.

5.2.2 Environment Analysis

The environment external to the MSDF/STA/RM system is a temporal universe in which evolve several entities that can directly influence the system, as well as each other. The outputs of these entities produce inputs to the system and possibly each other, and the outputs of the system produce inputs to these entities. This sub-task will:

- identify all entities that may be part of this environment in some scenario to be studied;
- determine the operations, significant events and system-entity or entity-entity relationships that can affect system or entity behaviour;
- determine all inputs and outputs for the system and each of these entities;
- describe the behaviour of each entity; and
- specify the timing constraints on the outputs of each entity and on the communication of these outputs to the system interfaces and other entities.

Aspects of the environment analysis that are specifically related to the user/operator of the MSDF/STA/RM system will be treated only briefly here as such issues will be examined in greater detail as part of a separate sub-task described later in Section 5.5. On the other hand, all other entities, including sensor, weapon, and own/friendly/hostile platform entities, will be

examined in more detail here. Sensor entities providing track or contact data to be considered will include long range radar (LRR), medium range radar (MRR), ESM, IFF, and IRST. A datalink entity will also provide radar, ESM and IFF track data. Hardkill weapon entities will include a SAM system, gun, CIWS, and fire-control radars. Softkill weapon entities will include jammers, chaff or flare rockets, rubber ducks, and active decoys. Target entities will include aicraft and anti-ship missiles with active radar, home-on-jam, anti-radiation or infrared seeker heads, and with a variety of flight profiles, including sea-skimmers, shallow-divers and high-divers. The results of the environment analysis will be used in Activity II as the basis for designing an MSDF/STA/RM system stimulator for the simulation environment to be developed there.

5.2.3 Functional Analysis

This sub-task will produce a functional decomposition of an MSDF/STA/RM system. The decomposition will be independent of technical constraints and technical solutions and will be done at a sufficiently detailed level to permit identifying potential design choices and functions which need further decomposition and input-output data flow specification to narrow down the choices in the design of a specific MSDF/STA/RM system.

5.2.4 Behavioural Analysis

The behavioural view of an MSDF/STA/RM system describes its dynamics as it evolves over time and reacts to perceived changes in the behaviour or the state of entities in its environment. It is concerned with concurrency and dynamic behavioural control of system components as well as with timing constraints on such control. The aim here is to produce a specification of the behaviour of an MSDF/STA/RM system in the integration framework.

5.2.5 Architectures

This sub-task will identify and model the overall software structure of an MSDF/STA/RM system. This structure and the timing requirements on recomputation rates of output flows and input-to-output response times for real-time transactions arrived at in the requirements definition will be used to propose candidate system architectures for the hardware-software co-design of an MSDF/STA/RM system. The system is to be viewed as a distributed system, with code running in multiple processes or threads on several RISC processors, with interprocessor communication links between the CPUs. Issues that will be addressed include mapping functional elements of the software architecture to processors in the hardware architecture and their scheduling requirements. Assessments of candidate architectures will be provided based on rough analyses only, taking account of hardware constraints on computation and communication bandwidth and of performance constraints such as timing. The conclusions of this work will be used to narrow the initial choice of architectures that need to be simulated in the simulation environment developed in Activity II and to identify potential processing bottlenecks that will require more careful empirical analysis in the implementation and validation stages of Activities III and IV.

5.3 Measures of Performance and Measures of Effectiveness

The emphasis here is on identifying and deriving measures of performance (MOPs) and measures of effectiveness (MOEs) for an MSDF/STA/RM system that are of a generic nature. Aside from their independent importance for the design and analysis of a command and control system, these MOPs and MOEs will be used in Activity II to derive a set of default measures to be monitored during experiments with the simulation environment developed there.

MOPs and MOEs for the overall MSDF/STA/RM system, and for each of its sub-systems, will be defined. Measures of performance of the MSDF sub-system are well known and can be found in numerous publications in the

open literature, as well as in Ref. 45. In general, MOPs and MOEs for the STA and RM sub-systems are less well known. They will be derived using the requirements definition and functional analysis of the generic STA and RM sub-systems developed during the work described in Subsections 5.2.1 and 5.2.3. Some candidate measures are summarised here:

- position, velocity, track quality;
- correct identification and allegiance (threat or not, etc.), group status, threat levels, mission of all air tracks and groups of platforms, interpretation of the tactical picture in general and at specific ranges and threat intentions; and
- diagnosis of unexpected events in the tactical situation and the plan validation verdict of plan monitoring and plan quality.

In addition, there are some obvious measures for the total performance of the MSDF/STA/RM system, such as the fraction of warships in the force damaged or destroyed and their average survival time, the fraction of air threats destroyed by hardkill or softkill weapons and the fraction that are leakers or free riders, the average range at which air threats are intercepted, the degree of overkill, the number of instances of fratricide, the fraction of nonrenewable resources (missiles, shells, chaff rounds, etc.) expended and the number of times the use of a hardkill weapon interferes with the use of a softkill weapon.

In addition, all measurements that would need to be taken during the operation of the MSDF/STA/RM system so as to obtain estimates of the various measures will be determined. This determination will not, however, be concerned for the moment with how such measurements would be taken or the specific data collection experiments that would have to be conducted to obtain these measurements.

5.4 Real-Time System Performance Measures

Similar to Section 5.3, the emphasis is on real-time system performance measures for an MSDF/STA/RM system that are of a generic nature. They will be used in Activity II to derive a set of default measures to be monitored during experiments in the simulation environment developed there.

As is well known, the correctness of a real-time system depends not only on the logical results of computations, but also on the time at which the results are produced. This task will identify and define a number of measures of real-time performance of the MSDF/STA/RM system, including :

- speed;
- timeliness;
- responsiveness; and
- graceful adaptation.

In addition, all measurements that would need to be taken during the operation of the MSDF/STA/RM system so as to obtain estimates of the measures will be defined, without concern, as in Section 5.3, for the method of their collection.

5.5 Human-Computer Interface (HCI)

The aim here is to study and document the interaction of the MSDF/STA/RM system with its user/operator. In particular, the following issues will be investigated:

- automated MSDF/STA/RM as a support and decision aid, including support requirements of the operator, various context-dependent modes

for the division of responsibility between the system and the operator, and decision-making protocols for the various modes;

- database management and query language; and

- integrated real-time display (data representation to the user).

This study will provide input to the requirements definition and environment analysis phases of the development in Section 5.2 of the integration framework for an MSDF/STA/RM system.

The investigation of an integrated real-time display will determine what information needs to be displayed, and how. There is a need to consult CPF and TRUMP operators about recommendations for a suitable HCI interface.

6.0 ACTIVITY II: DEVELOPMENT OF A SIMULATED REAL-TIME ENVIRONMENT (SRTE)

The performance of a complex, distributed real-time system like an MSDF/STA/RM system is heavily influenced by numerous factors whose effects are extremely difficult, perhaps even impossible, to accurately model in a theoretical analysis. However, simply proceeding to implement a specific system design on existing COTS technology and "seeing whether it works" is far from satisfactory as a first step. Some of the particularly serious shortcomings of this approach are as follows.

- The approach is costly and inflexible. This has the effect of severely limiting the range of design choices and variety of possible system environments that can feasibly be explored and analysed.

- When performing a detailed analysis of critical timing behaviour, it can be extremely difficult, and in many cases impossible, to obtain valid performance measurements based on software-driven probing mechanisms in a "live" distributed system since they are intrusive and can disturb timing relationships that may be crucial to system performance. For example, obtaining any kind of measurement from a running program implies executing some extra monitoring code either at the program or at the microcode level, which has the effect of distorting actual execution times. Such distortions may change the observable behaviour of the system, leading to invalid conclusions about its performance. While the introduction of special-purpose hardware in the form of specialised co-processors for the non-intrusive collection and post analysis of system run-time information can address some of these problems, this approach lacks the flexibility and power for the detailed analyses that are required at the algorithm level.

- The approach does not easily permit repeatable testing of a distributed system for purposes of problem diagnosis and performance tuning because

of its nondeterministic nature: the same system implementation may produce different results across different runs of the same scenario.

- Finally, it is difficult to reliably extrapolate performance results to account for the effect on total system performance of future developments in weapon and sensor system technologies and in processor and interconnect technologies.

The purpose of this activity is to specify, design and implement a high-performance, versatile environment running on a host workstation that provides a simulation-based "specify-explore-refine" approach to resolving all of the problems mentioned above. This environment will enable all work toward specification, design, prototyping and validation of MSDF/STA/RM systems developed in Activities III and IV to be done using this environment. Development and validation of real-time system prototypes running on existing (i.e., non-simulated) COTS technology, which is a logical next step along the path toward the eventual fielding of a prototype MSDF/STA/RM system, is not a goal, however, of the current work.

The simulated real-time environment (SRTE) developed here will satisfy a number of general design goals. Brief statements of some of these goals are now given, followed by descriptions of specific key sub-tasks consistent with these goals that will be undertaken as part of the design and implementation of the environment.

- SRTE will be a hardware-software-environment discrete event co-simulator. Specifically, it will simulate the real-time execution of a user-specified MSDF/STA/RM system running on a user-configured target hardware architecture, interacting with its user-specified system environment. Its simulation engine will interleave in simulated time, subject to causality constraints and in time-stamped order, machine-level events associated with the execution of code running on the processors of the target hardware, including the communication between threads running on the same processor or on different processors, with events that

arise from interactions between the MSDF/STA/RM system and its environment.

- SRTE will permit the user to control the level of accuracy of the simulation of hardware, software, and system environment elements as a means of trading off the accuracy of the simulation for increased performance. High-performance simulation at all levels is an important goal to permit analysing in a controlled manner the behaviour of an MSDF/STA/RM system or its various system components in open-loop and closed-loop experiments involving nontrivial combat scenarios.

- The methodology for specification and design of a generic real-time MSDF/STA/RM system and integration framework developed as a result of the work in Activity I will be integrated into SRTE. This integration will permit all phases of system specification, design, implementation and validation to be conducted in the environment and it will eliminate, or at least minimise, discontinuities that arise between these phases. As illustrations, there will be support to enable a user to create and edit system specifications and designs; also, having created a system design in SRTE, to debug and profile code designed to run on a user-configured target hardware architecture, as well as to replay simulation runs of the system from simulation trace files, and so on. Ideally, SRTE should also allow for source-code compatibility to permit automatically generating code for a real COTS machine consisting, for example, of a network of RISC workstations or a parallel machine.

- SRTE will provide tools for monitoring and analysing the effects of system design choices. It will be designed with a modular structure to simplify replacement and customization of its parts; for example, there will be flexibility to easily customise the target architecture on which an MSDF/STA/RM system is to run, or to develop and test multiple implementations of some functional element in the system, and so on.

A high-level view of the simulation environment is given in Fig. 13. A C2 software system, which could be the MSDF/STA/RM system itself or some sub-system, is shown being simulated as it runs on a hypothetical hardware environment and interacts with a simulated external environment. The sub-tasks within this activity that lead to the design and implementation of SRTE's components illustrated in this figure are described below.

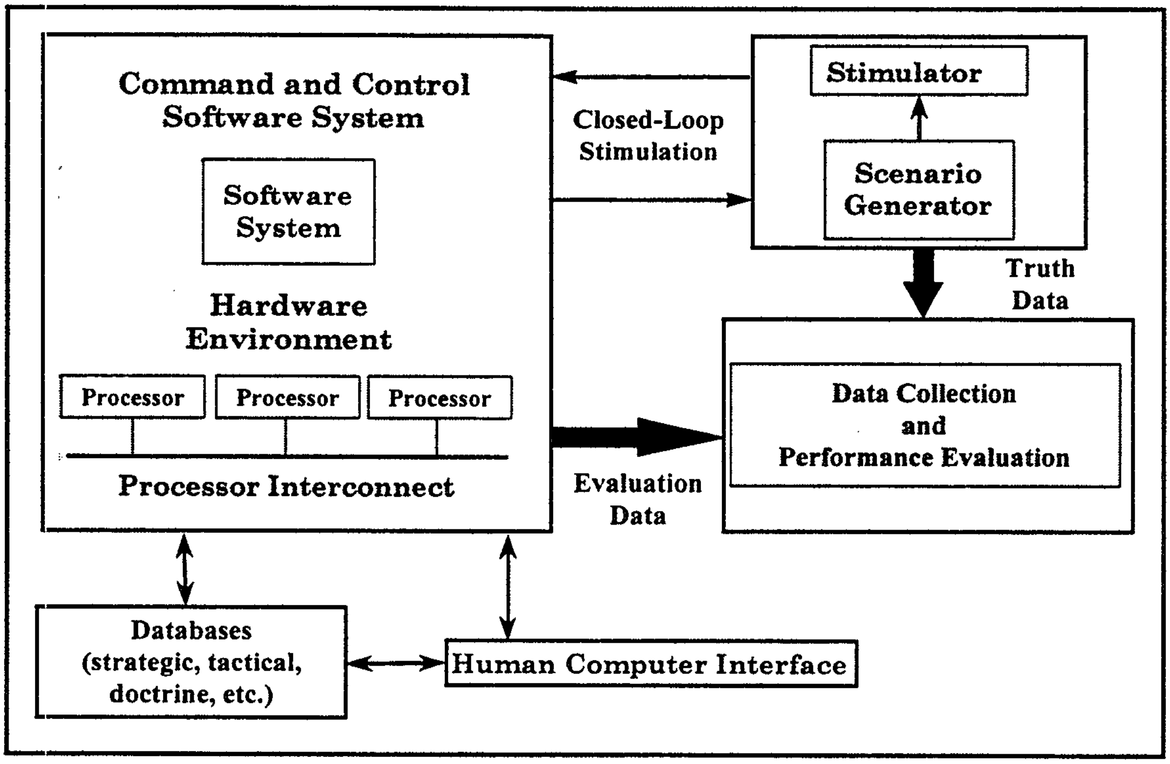

FIGURE 13 - SRTE high-level framework

6.1 Specification and Design

6.1.1 Simulated Real-Time Performance Evaluation Methodology

This sub-task will define the details of a methodology based on a "specify-explore-refine" paradigm for the hardware-software co-design of an MSDF/STA/RM system. An essential feature of this methodology will involve

co-simulating the real-time behaviour of the software of the system, the hardware on which it runs and the environment with which it interacts. Specific issues to be addressed include specification validation, design validation, design of simulation experiments, performance monitoring, performance profiling, data collection and analysis of results. Statistical aspects of the various system validation experiments will be defined, including the data collection experiments that need to be conducted, the measurements to be made, and how, and the tests to be performed to obtain statistically significant conclusions about the behaviour of the simulated system or estimates of its various MOPs, MOEs, and real-time system performance measures. Specific features of the methodology for detecting violations in system requirements (timing constraints, accuracy of some function, etc.) will also be developed.

6.1.2 Integration Framework for a Generic MSDF/STA/RM System in SRTE

The results of the work described in Subsection 5.2 will be used to define the framework for a generic MSDF/STA/RM system that will be implemented in SRTE. This framework will encompass essentially the core portions of an MSDF/STA/RM system. It will support a multi-level and hierarchical approach to system modelling to facilitate creation, editing, replacement, customization and extension of the specification and design of an MSDF/STA/RM system in explorative studies using SRTE.

6.1.3 MSDF/STA/RM Environment Modeling and Analysis

The results of the work described in Subsection 5.2.2 will be used to develop models for simulating the real-time behaviour of each entity that may be part of the environment of an MSDF/STA/RM system in SRTE. Each simulation model of an entity will be analysed along various performance dimensions, including its computational requirements, its accuracy in modeling the behaviour of the entity, and its ability to produce time-stamped outputs whose time-stamps satisfy timing constraints on such outputs. A

variety of models will be developed for each entity of differing performance capabilities to permit trading off accuracy in the simulation of an entity for increased simulation runtime performance. This sub-task will also investigate the potential of using in SRTE, either directly or by appropriate modification, various sensor models already implemented in DREV's CASE_ATTI algorithm-level testbed for MSDF (Ref. 46). The same will be done for various weapon, target and ship models currently used in DREV's anti-air warfare simulator (Refs. 45-47).

6.1.4 CASE Tool for Real-Time System Specification and Design

This sub-task is concerned with the integration in SRTE of the methodology, developed in Activity I, for specification and design of a real-time MSDF/STA/RM system, as well as with the details of the support that will be provided to permit a SRTE user to create and edit system specifications and designs. This integration will be consistent with the goal of enabling all phases of system specification, design, implementation and validation to be conducted in the environment.

The requirements of a CASE tool that can provide solid support for the methodology, specification and design review, consistency checking and reusability of specifications and generation of code and documentation will be determined. The CASE tool will either be designed or be selected from a commercially available tool that satisfies the requirements, depending on which solution is judged the more cost-effective.

6.1.5 Simulation Strategy

This sub-task will define the technical details of a discrete event sequential simulation strategy for the hardware-software-environment co-simulation of the real-time execution of a user-specified MSDF/STA/RM system running on a user-configured target hardware architecture, interacting with its user-specified system environment.

An essential element of the strategy will be the use of techniques for reducing simulation overhead. Two types of techniques will be included. Among the first type are techniques that increase simulation performance without (significantly) sacrificing the accuracy of a simulation. The second type involves making tradeoffs in the accuracy of the simulation of hardware, software or system environment elements for increased simulation performance.

One important example of the first type of technique that will be part of the strategy is the use of direct execution on the host platform of instructions in a software component, including the MSDF/STA/RM system, runtime system and function library components, that are local to some processor of the simulated platform, as a means of providing very low overhead simulation of code (specifically, those portions of the code that do not interact with other parts of the simulated system). The key idea here is to execute such local instructions directly, following a preprocessing step that augments basic blocks at the assembly language level with cycle-counting instructions that account for the passage of simulated time during their execution on the simulated hardware. In the literature, this novel simulation technique is also referred to as execution-driven or compiled simulation and it has been used recently in a number of high-performance parallel architecture simulators available in the public domain, including RPPT (Ref. 50), TangoLite (Ref. 51), PROTEUS (Refs 52-54), and FAST (Ref. 55).

Another example of a technique of the first type is the use of lightweight threads as a means of reducing the cost of context switching between software threads during their simulation.

The second type of technique is related to the use of multiple versions of simulation models for elements of the system environment or hardware. Environment examples are provided by the work in Subsection 6.1.3. An example in the hardware case is a detailed packet-by-packet simulation of the interconnect between the processors of the simulated hardware versus use of a less accurate analytical model that allows for network contention

based on specific assumptions about the distribution of interconnect load or an even less accurate, but extremely simple, constant delay model that does not account at all for interconnect contention.

6.1.6 Architectural Models

The results of the work in Subsection 5.2.5 will be used to identify specific hardware models to be represented in SRTE. These models will consist of a number of architecture simulation components that simulate the three main parts of a user-configured hardware architecture on which an MSDF/STA/RM system is to run: processors, memory and interconnects. The user will be able to choose from potentially different representations of each part; in addition, each component will provide the user with several architectural parameters that can be set to fine-tune a specific configuration to a given target hardware on which the simulated real-time performance of a system is to be evaluated. A processor node will consist of a generic RISC processor, memory (including a cache) and a network chip which provides access to the interconnect and, depending on the interconnection model, acts as a router. Communication between a simulated processor and other parts of the system, including the system environment interfaces, will use either shared-memory or (interrupt-driven) message passing. A shared-memory model (with cache coherence) will therefore be part of the memory model. Both bus and network interconnection models will be supported.

6.1.7 Programming Model

There are three requirements on a programming model to be used for representing all software components of a user-specified MSDF/STA/RM system in SRTE:

- it must be sufficiently low-level to permit controlling the behaviour of a simulated hardware component at the level of the simulation;

- it must be sufficiently high-level to be used directly by a programmer; and

- it must be compatible with code generated by the CASE tool designed (or identified) in Subsection 6.1.4.

In this sub-task, a programming model based on augmenting a standard high-level language with a set of low-level simulator calls and a number of language extensions that satisfies these requirements will be defined.

6.1.8 Knowledge-Based System (KBS) Technology

This sub-task will first investigate and define the requirements of a rule-based KBS shell that can be integrated into the SRTE environment and used to build KBS components of an MSDF/STA/RM system for purposes of simulated real-time performance evaluations. These requirements will include a framework for representing and performing inference on domain knowledge (including mechanisms for forward chaining and backward chaining), and (at least) one robust method for handling knowledge and information uncertainty, chosen from fuzzy logic and fuzzy reasoning, truncated Dempster-Shafer theory, Mycin uncertainty calculus and probability theory. A KBS shell will subsequently either be designed or be selected from a commercially available KBS shell that meets these requirements. The choice will be made, based on a determination of the option that leads to the more cost-effective solution.

6.1.9 Real-Time Runtime System

This sub-task will first investigate and define the requirements of a real-time runtime system for the node processors of a distributed MSDF/STA/RM system. This investigation will concentrate on the real-time response characteristics of the runtime system, including its execution model (i.e., task/thread definition and scheduling), memory model and dispatch latency. Other aspects, related to I/O handling and file system management, will be considered at the level of detail specifically required for the remainder of the work in this sub-task. The results of this investigation will be used to

design a detailed model of a small real-time runtime system that is to run on every node processor of a user-configured simulated hardware architecture in SRTE and provide basic services, such as thread and memory management. This model will be built on top of the programming model defined by the work in Subsection 6.1.7. This is to allow the performance cost of runtime system routines to be accurately calculated by cycle-counting their code at simulation time using the code augmentation technique described in Subsection 6.1.5. The model will be sufficiently modular to permit easy replacement or customization of its parts in studies aimed at experimenting with different scheduling algorithms and strategies, as well as other runtime system issues.

6.1.10 Scenario Generator

Based on the nature of the scenarios considered in this project, a scenario generator that takes as input user-determined values chosen from a parameter set and then randomly generates scenarios with the required characteristics for use in SRTE performance evaluation studies will be designed. The features of a scenario generated in this manner are those that can be described statically (i.e., prior to running a simulation experiment in SRTE). Other features that depend on runtime interactions with an MSDF/STA/RM system will be handled by the stimulator designed as a result of the work described in Subsection 6.1.11.

6.1.11 Stimulator

The results of the system environment analysis conducted in Subsection 5.2.2 of Activity I and the entity models developed in Subsection 5.1.3 will be used to design a stimulator for SRTE that simulates the behaviour of the system environment as it interacts in a closed-loop manner with a user-specified MSDF/STA/RM system running on a user-configured target hardware architecture. The design of this stimulator will need to be consistent with the simulation strategy developed in Subsection 6.1.5 to permit its integration into the SRTE environment for performance evaluation

studies. In addition, its framework will be sufficiently modular to permit easy replacement, customization or extension of existing environment entities, as well as the creation and integration of new entities.

6.1.12 Nonintrusive Performance Monitoring

SRTE will provide a number of nonintrusive performance monitoring features at the level of a user-determined code segment that enhance flexiblity in simulation studies using the environment. These features include: code profiling to permit a user to track the number of times a code segment is executed by each processor of a simulated hardware architecture or the total number of processor cycles spent executing this code; turning cycle counting on or off on a code segment to allow the addition of debugging or monitoring code without introducing a probe effect into a simulation experiment; and explicit user-control of the cycle counter, if desired, on a code segment.

This sub-task will incorporate the features described above into the code augmentation technique that is part of the simulation strategy developed in Subsection 6.1.5. In addition, a tool, that is part of SRTE, will be designed for automating the process of creating a statistical database, with respect to a given set of inputs, of runtime profiles (in terms of processor cycles) of a code segment implemented in SRTE.

6.1.13 Debugging

This sub-task is concerned with designing features aimed specifically at providing support to the user for debugging an MSDF/STA/RM system implementation in SRTE. Starting from the capability provided by a standard sequential debugger compatible with SRTE, additional features will be incorporated that extend this capability in directions important for implementing a distributed MSDF/STA/RM system in SRTE. Such features will include the ability to examine snapshots of the state of a software

component or a simulated machine running a code segment, to replay a part or all of simulation from a simulation trace file, livelock detection, and so on.

6.1.14 Data Collection, Graph Language and Graph Generator

The ability to collect and display data in simulation experiments or replay a simulation run is an extremely important requirement of SRTE. This sub-task is concerned with defining various data collection and display tools for these purposes.

A framework for generating trace file data during a simulation run in SRTE will first be developed. Predefined trace file data will be automatically collected during a run to permit monitoring the various default MOPs, MOEs and real-time system performance measures identified by the work in Sections 5.3 and 5.4 or to allow replaying a simulation run (see also Subsection 6.1.13). The user will also be able to generate his/her own trace file data (by embedding appropriate data collection statements in system code) to permit monitoring user-defined MOPS, MOEs and real-time system performance measures specific to his/her simulation experiments. This framework will be capable of generating both time-independent data (metrics) and time-dependent data (simulation events).

A framework for postprocessing trace file data produced in a simulation experiment in SRTE to generate a variety of performance graphs, including line graphs, bar graphs, and tables, and to combine multiple graphs from one or more trace files produced in several experiments onto the same axes will then be defined. A number of predefined graphs will be automatically provided in SRTE. In addition, a graph language will be designed to permit a user to create new graph specifications.

6.1.15 User Interface and Simulation Configuration Manager

This sub-task is concerned with the design of a user interface as a single control point for managing real-time simulation experiments in SRTE.

This interface will provide capabilities for controlling function-, system architecture-, target architecture-, run-, scenario-, and stimulator-specific parameters. For example, based on a specific MSDF/STA/RM system architecture which the user configures, he/she may also select from multiple versions of various functions in a library; or when testing the implementation, the user may configure a target hardware architecture and a mapping between MSDF/STA/RM functions and some node processor or group of node processors of the target platform on which the function is to run in the present simulation; or the user may specify that a run is to simulate events that occur during a particular period of simulated real-time (with an appropriate signal when the run terminates) or that certain system components are to be simulated at a low level of accuracy as a means of reducing simulation overhead during the run; or when compiling performance statistics, the user may select a sample of scenarios for each of a number of instances of a certain type of scenario to initiate multiple simulation runs without need for further user involvement during the course of the runs; and so on.

6.1.16 Software Architecture

Based on the results of the sub-tasks described above, a software architecture will be designed for integrating all of the previously designed components into a common operating environment satisfying all SRTE requirements. A particular objective is to design an environment that permits all phases of system specification, design, implementation and validation of an MSDF/STA/RM system to be conducted in this environment without introducing discontinuities into the modelling process.

6.2 Implementation and Validation

In this sub-task, the SRTE design will be implemented and validated. Limitations on the nature and scope of the various MSDF/STA/RM open-loop or closed-loop simulation studies (e.g., size and duration of scenarios) that can be conducted using this implementation of SRTE due to inordinate

simulation overhead or memory and performance limitations of the host machine will be determined.

7.0 ACTIVITY III: CAPTURE OF REAL-TIME REQUIREMENTS FOR A BASELINE MSDF/STA/RM SYSTEM

Various theoretical analyses and proof-of-concept simulations of different types of MSDF/STA/RM techniques have already been conducted by DREV and its contractors and collaborators from industry and university. These studies have analysed and demonstrated a variety of approaches, algorithms and techniques for the CPF, and identified their advantages and disadvantages and established their tradeoffs. However, certain MSDF/STA/RM techniques required for the CPF remain to be fully implemented and analysed. Some previously implementated techniques also need further evaluation for their suitability in a real-time implementation. Finally, the important aspect of designing a fully integrated, real-time MSDF/STA/RM system has not yet been addressed.

This activity will capture and analyse real-time solutions to the various problems of the CPF. These analyses will lead to the specification and design of a baseline MSDF/STA/RM system onboard a single ship acting in point defence operations. Techniques that permit the use of remote target data received by tactical data links as an additional source of information in performing ownship self defence will also be part of the design. All exploratory work concerned with the specification, design, prototyping and validation of the baseline system will be conducted using SRTE. Refinements and extensions to the baseline design that are required to support area defence or wide area multi-platform operations will be analysed and demonstrated in Activity IV that follows.

7.1 Specification and Design of a Baseline MSDF/STA/RM System

This task is divided into four sub-tasks. There is one sub-task for each of the three real-time system components, MSDF, STA, and RM. Their results are then used in the fourth sub-task to specify and design the baseline integrated MSDF/STA/RM system.

7.1.1 Identification and Selection of Candidate MSDF Sub-Systems

An explicit definition of the MSDF process for the CPF will first be developed, and then followed by an investigation of the relevant MSDF approaches and algorithms to deal with single platform real-time requirements. An assessment of the real-time applicability of the MSDF R&D studies conducted at DREV will then be made. The various MSDF components developed by DREV will be combined and the missing capabilities required to support a complete single platform MSDF function identified. Various approaches for providing these missing capabilities will be developed and evaluated using the existing components of DREV and those of its contractors.

The knowledge and expertise obtained from existing DREV studies and those of its contractors' previous studies will be combined to generate a specification for each of the following functions: Data Alignment, Data Association, Kinematic Data Fusion, Target State Estimation, Target Kinematic Behaviour Assessment (i.e., type of maneuver, etc.), Target Attribute Estimation/Fusion, Identity Information Fusion and Track Management Process (i.e., initiation, confirmation, deletion, etc.). The relative performance of the various techniques will be evaluated for scenarios generated by the scenario generator in SRTE.

Analyses which consider data from all sensors onboard the CPF and remote Link-11 data will be conducted. This data is used as additional information to derive target kinematic and identification estimates for onboard tracking. Multi-platform issues involving the Wide Area Tactical Situation (WATS) will be examined later as part of Activity IV.

The nature, accuracy, and frequency requirements of the input and output data for each individual function and technique, along with its robustness to the operational environment will be specified.

A set of MSDF sub-system configurations will be identified, specified and analysed by selecting and combining appropriate candidate techniques previously studied, and based on an analysis of their expected performance at the system level. Practical MSDF system examples that are of interest for the CPF will be studied to help provide recommendations about MSDF configurations that are best suited for the CPF application.

7.1.2 Situation and Threat Assessment

This sub-task will include the following:

- cluster analysis for a single ship in preparation for situation interpretation;
- knowledge acquisition for the threat assessment function of situation interpretation; and
- the design of a real-time rule-based KBS for the threat assessment function.

The occurrence (or absence) of a particular event does not necessarily indicate a problematic situation. In other words, the meaning of a particular event must be interpreted in relation to the current state of the world, as well as its past history and expected future. For example, simply identifying a foe in the tactical picture does not necessarily lead to offensive actions. First, the situation must be assessed by considering the presence or absence of other friends or foes in the area, the weapons available on-board to attack the foe(s), the weapons that the foe could use against the ship, etc. There are different ways of performing these assessments (i.e., situation interpretation and prediction). In this sub-task, real-time implementations of knowledge-based methods for performing situation interpretation will be proposed and evaluated. These implementations will:

- evaluate threat capabilities and actions; and

- infer threat actions.

7.1.2.1 Cluster Analysis for a Single Platform

In preparation for situation interpretation, criteria for grouping tracks according to geometric proximity will be developed. Temporal relations and dependencies of tracks for general air defence scenarios (e.g., mixed types of aircraft, helicopters launching anti-ship missiles, long range and short range anti-ship missiles launched from air or surface platforms) will be enumerated, and similar events of these air tracks will be classified so that they can be grouped together by event. In enumerating the dependencies of air tracks mentioned above, specific attention will be paid to functional dependencies perceived among air tracks that enable forming groups of tracks having similar function or similar origin.

7.1.2.2 Knowledge Acquisition for Situation Interpretation

This sub-task will carry out knowledge acquisition for the situation interpretation knowledge bases. Knowledge acquisition of different aircraft, helicopter and anti-ship missile types will be conducted so that real-time knowledge bases, constructed using design-to-time or anytime algorithms, can provide a situation interpretation to the CO in real time.

Knowledge in rule form on target threat characteristics (identity, manoeuvres, kinematic parameters, engagement status) will be compiled, as well as rules on doctrine, target distribution (raid size), countries of origin, platform mission, target lethality, electronic emissions, tactical activities such as jamming, likely outcomes of engagement actions, target emitter status (on/off) and target radar mode (acquisition, tracking). The identity information coming from MSDF will be to decide how much of it can be used in this knowledge acquisition study.

A threat assessment function, consisting of sub-functions for track behaviour, threat evaluation and threat prioritization, will be studied. Ways

of deducing the activities (behaviour) of air platforms will be investigated. Particular attention will be paid to compiling knowledge which will decide whether the air platforms are conducting surveillance, reconnaissance, bombing, launching anti-ship missiles (ASMs), or over the horizon targeting for ASM platforms. Threat evaluation consists of taking the factors described in the second paragraph above and deciding the extent to which the air track or tracks constitute a threat to the ship. A threat evaluation function will be built from this knowledge. A threat prioritization function associating numerical threat levels with each of the states described by the track behaviour will be designed, as well as threat evaluation functions for which knowledge acquisition has been conducted. Research will be done in associating a global threat level with a group of hostile tracks. The effect of allegiance and the social political context (war or peace) on the knowledge required for situation interpretation will be investigated.

7.1.2.3 Development of Situation Interpretation KBSs

After or at the same time an identification has been made of all air tracks in the ship's air track database, situation assessment must make an interpretation of what occurs in the airspace surrounding ownship. The re-assessment of the situation interpretation must be dynamic and occur in real time to cater to a changing environment as new data is acquired.

Knowledge-based inferencing schemes and hypothesise and test procedures to produce real-time algorithms that interpret the current tactical situation will be studied. Situation interpretation means that the CO must know whether he/she is confronted with an aircraft group, a helicopter group or a mixed group of air platforms, whether these platforms are about to launch anti-ship missiles on the ship, whether they are likely to use unguided or guided bombs against the ship or whether they are likely to use stand-off weapons. He must also know whether they are doing reconnaissance or simply spying. The intentions of all air tracks must be made known to the CO in real time. One of the following two possibilities will be pursued. Either real-time knowledge-based systems will be built that

infer the intentions of the air tracks in real time by the use of a suitable inferencing scheme or hypothesise and test procedures in the knowledge-based system will be built that do the above situation interpretation in real time.

Because of the difficulty of obtaining a correct situation interpretation, based on uncertain or incomplete information, the use of robust uncertainty methods such as fuzzy reasoning and fuzzy logic, Mycin uncertainty calculus and probability theory for addressing this problem will be investigated.

The situation interpretation knowledge bases will be designed by using the results of the knowledge acquisition described in Subsection 7.1.2.2. The effect of allegiance and the social political context (war or peace) on the results obtained from the situation interpretation KBS will be investigated.

7.1.2.4 Specification and Design

A design specification for a STA sub-system that includes functions for kill assessment, force resource evaluation and engageability effectiveness will be developed.

A kill assessment function for hardkill weapons will be integrated with the threat assessment function developed by the work described in Subsections 7.1.2.2 and 7.1.2.3. A rule-based system to do kill assessment in real time for surface-to-air missiles, naval guns and a close-in-weapon system will also be designed.

Knowledge-based systems that assess ownship status in real time will be designed. A real-time knowledge-based system that estimates the operational status of shipboard weapons, depending on their availability, ammunition level and reserved stock levels will be designed for the case of a single ship attacked by air threats. A real-time knowledge-based system to determine which hardkill weapons (surface-to-air missiles, naval gun, close-

in weapon system) can feasibly engage a target in the track database will also be designed. As well as containing track engageability rules, this real-time KBS will contain rules for determining the effectiveness of hardkill weapons against air threats. Appropriate rules concerned with probabilistic estimates of the effectiveness of each hardkill weapon against each type of air threat will be included.

7.1.3 Resource Management for Hardkill Weapons

To establish a firm context for the work in this sub-task, the purpose and nature of the resource management (RM) sub-system in an MSDF/STA/RM system for the CPF is first reviewed.

The purpose of the RM sub-system is to provide real-time planning and decision support to aid naval personnel with the coordinated use of critical defence resources and to optimise the ship's defensive capabilities. From the perspective of real-time combat management, this decision making concerns the control and operation of a variety of the ship's sensors for refining and enhancing perception of the tactical situation (sensor management), as well as the coordinated use of its hardkill and softkill weapon systems to counter threats. In practice, however, other decision-making aspects, related to the management of other resources (computation and communication bandwidth of the ship's hardware platforms, the electromagnetic spectrum, etc.), also need to be considered as they affect or constrain the operation of RM.

RM is a closed-loop process that continually interacts with human operators (the Command Team) and an environment consisting of a time varying number of dynamic entities. Human interaction can take the form of commands and/or requests for support. This may entail informing or advising the operator by providing recommendations, suggestions, etc., depending on support requirements and on the division of responsibility between RM and the operator. The need to synchronise actions with

occurrences in the combat environment can impose critical timing constraints on the temporal behaviour of the various subprocesses of RM.

RM can be described in a little more detail as follows. Situation and threat assessments from the STA sub-system, together with human interaction via the HCI, as required or as response time permits, drive the planning and decision support functions in RM. In a given situation, planning a course of action (a specific resource allocation) involves reasoning in time and about time. These decisions may be required periodically (e.g., as a result of sensor input) or aperiodically (e.g., due to sporadic interactions with the operator). Finally, RM is the continuous process of planning, coordinating and directing in real time the use of the ship's resources to counter the threat.

RM work in this project will be primarily related to the specification and design of a weapon engagement manager (WEM) for the Above-Water Warfare (AWW). The WEM is the specific component in the RM sub-system of a real-time MSDF/STA/RM system responsible for supporting the Command Team in planning, managing and effecting all actions associated with the use of hardkill and softkill weapon systems, including providing recommendations of ship manoeuvres for clearing blind arcs in support of engagements or for improving weapon effectiveness.

Previous DREV R&D (Refs. 56-57) has already developed a high-level specification of a WEM, including its software architecture. In this specification, the WEM continually adapts its reasoning to account for an evolving tactical situation, available computational resources, response time and the interdependence between planning and the quality of information. Plan quality is traded off against computational cost and response time. The software architecture has a top layer, where a deliberative planner and chooser reside, and a second lower layer (closer to situation data and available weapons), which consists of a projector, a characteriser and an effector. The design approach integrates both deliberative and reactive planning by coupling feedback and feedforward control to permit dynamic

interleaving, and even overlapping, of incremental planning and execution of plans. The roles of the principal components in this architecture are described below.

The deliberative planner responds to significant changes in the tactical picture that require (re)planning. It computes a plan, subject to engagement doctrine, resource availability and other constraints determined by the operator, for assigning and scheduling weapon systems and tracking and guidance systems to counter threats. It is possible for several planning functions to be integrated into the planner, differing according to their capability, type of reasoning mechanism employed (e.g., based on precompiled domain knowledge or a mathematical model such as a decision-theoretic or utility-driven planning model) and computational complexity.

The chooser, interacting with the operator according to some decision-making protocol, then selects from the various plan options. Recognizing significant changes in the tactical picture is handled by the characteriser based on inputs from the STA sub-system, using its internal model of the world and information from the projector and the effector. This model permits non-monotonic and probabilistic reasoning about change and the effects of actions and their effectiveness.

The projector maintains information corresponding to extrapolations of the perceived historical states of the world. Projection can include:

- extrapolating potentially hostile tracks and ship manoeuvres;

- predicting occurrences of events arising from ongoing engagements, previously committed actions, etc., including outcomes of defence actions and threat strikes on ownship;

- predicting when potentially hostile tracks will be engageable and by which weapon systems, as well as measures of effectiveness of such defensive actions;

- predicting effects or restrictions associated with obstructions (parts of the ship's structure, chaff clouds, offboard decoys, etc.), environmental conditions or operational constraints (EMCON, risk of fratricide, etc.) which prevent threat interception, or which, at least, significantly degrade effectiveness of such actions; and

- predicting positive and negative interactions that result from concurrent use of hardkill and softkill weapon systems.

By communicating with weapon controllers, the effector coordinates and directs execution of plans. It is driven by precompiled stimulus-response knowledge (reactive behaviour) that provides almost immediate response as needed. However, it is also guided by deliberative input from the chooser.

This sub-task will restrict the focus of the WEM to the use of hardkill weapons only, on the CPF acting in point defence operations. Broadening this focus to encompass resource management issues that arise in area defence and wide area multi-platform engagements, and with using softkill weapons and their integration with hardkill, and so on, will be done later as part of Activity IV.

7.1.3.1 Specification of a Weapon Engagement Manager

Following the methodology developed in Activity I, and based on an analysis of the existing DREV model of a WEM, including its software architecture, a complete specification of a WEM for hardkill weapons for the CPF will be provided. Particular attention will be paid to incorporating any components (e.g., a meta-controller) necessary to make tradeoffs in the reasoning so as to achieve an effective real-time system design. This specification will also be consistent with the framework for integrating MSDF, STA, and RM already established as part of Activity I.

7.1.3.2 Algorithms for a Weapon Engagement Manager

A complete and thorough study and analysis will be made of models and algorithms required to implement the specification determined by the work described in Subsection 7.1.3.1. The results of this work will lead to a proposal for specific models and algorithms to be implemented and tested in a prototype of the WEM in SRTE.

Model analysis will examine in detail issues concerned with achieving real-time implementations of associated algorithms. For example, a variety of techniques and concepts in the real-time AI and the real-time systems literature useful for establishing predictable performance tradeoffs in algorithms to enable them to cope, when required, with computational resource limitations and a variety of response-time specifications, will need to be investigated. These techniques and concepts will include anytime algorithms for searching a problem space and for inferencing in a knowledge-based system, design-to-time or multiple methods, imprecise computation, and progressive deepening.

As part of the work in preparation for implementing the prototype WEM, a detailed analysis will be made of a specific DREV model and algorithms for planning both SAM firing and guidance actions against ASMs over some plan horizon. In this utility-driven model (Refs. 56-57), a plan is a conditional schedule of potentially concurrent SAM engagements over the plan horizon. The resulting planner is time-dependent in the sense that it varies its deliberation according to time pressure, by using a rolling plan horizon whose size is determined at runtime. DREV algorithms for the model include sequential algorithms and Multiple Instruction Multiple Data (MIMD) parallel algorithms for searching the space of feasible plans (Ref. 57). This model and its algorithm for computing solutions will be extended or augmented, as necessary, to handle the planning of all hardkill engagements on the CPF. Other sequential or parallel algorithmic approaches to computing plans will also be investigated, including various heuristics or

metaheuristics such as simulated annealing, tabu search, genetic algorithms, neural networks, etc.

A generic low complexity greedy unconditional planner will be implemented and used as a performance baseline in comparative assessments of the various algorithms for the planning component in the WEM.

7.1.4 Development of an Integrated Baseline MSDF/STA/RM System

7.1.4.1 Specification and Design

In this sub-task, the integration aspects of the selected and developed algorithms and architectures from Subsections 7.1.1, 7.1.2 and 7.1.3 for MSDF, STA and RM, respectively, within the overall MSDF/STA/RM system, will be evaluated. The integration framework developed in Section 5.2 will provide the basis for developing the integration. It will include specifications of the control and data flows, as well as their timing requirements, between:

- the MSDF function and the various STA components;
- the various STA components and RM capabilities;
- the MSDF function and RM capabilities; and
- the MSDF/STA/RM system and its environment.

It will also analyse the tradeoffs between concurrent implementation strategies for the various capabilities to achieve real-time performance.

This work will lead to a preliminary specification and design of a baseline MSDF/STA/RM system for the CPF (or a CPF-like ship) which will provide the starting point for the work to be performed in Sections 7.2 and

7.3. For example, there may be many candidates in the preliminary specification for specific algorithms and architectural components to be considered and further analysed before the final specification can be produced.

7.1.4.2 Identification of Performance Measures

The generic MOPs, MOEs and real-time system performance measures defined in Sections 5.3 and 5.4 will be considered to identify and derive any additional ones that need to be evaluated for the baseline MSDF/STA/RM system.

7.2 Implementation and Validation of Baseline MSDF/STA/RM System in SRTE

The most promising MSDF/STA/RM algorithms and architectural components will be chosen and implemented in the preliminary baseline MSDF/STA/RM system specified in Subsection 7.1.4.1. All software implementation and validation of this preliminary baseline system will be done in SRTE.

7.3 Capture of Real-Time Requirements for Baseline MSDF/STA/RM System

The "specify-explore-refine" methodology for the hardware-software co-design of an MSDF/STA/RM system developed in Subsection 6.1.1 and the generic and additional MOPs, MOEs, and real-time system performance measures will be used to capture the real-time requirements of the baseline MSDF/STA/RM system. The ultimate end product of this work is an implementation in SRTE of the baseline that has been validated using SRTE's monitoring and data collection capabilities as satisfying all real-time requirements of the MSDF/STA/RM system. A number of hardware and software parameters in the system design space will be explored to achieve this goal, such as the number of processors used and their computational

power, communication bandwidth, strategies for controlling and scheduling numerical and reasoning processes, various allocations of these processes to processors and their parallelizations, and so on. Questions of how much computational capability is required, and where, will also be analysed and answered.

Any limitations in the implementation of the baseline in SRTE, versus what can be expected of an operational MSDF/STA/RM for the CPF or an advanced CPF-like frigate class ship, built using the baseline specification, or in the experiments conducted using SRTE, or in the SRTE implementation itself, will be described. In addition, the impact of these limitations on the conclusions that have been drawn about the real-time performance of the baseline will be described and analysed. Sensitivity analysis experiments (using SRTE) is one technique that will be used to assess the extent of some of the limitations that are identified.

8.0 ACTIVITY IV: MSDF/STA/RM REFINEMENTS AND EXTENSION TO MULTIPLE PLATFORMS

This activity will re-visit the baseline MSDF/STA/RM system for the CPF, developed in Activity III, and will develop and evaluate refinements or extensions of concepts, models, algorithms, and architectures that have the potential to lead to enhanced functionality and/or improvements in the baseline system. It will also develop an extended MSDF/STA/RM integration framework that includes functions in support of area defence and wide area multi-platform operations. This will lead to the specification, design, prototyping and validation of an extended MSDF/STA/RM system in SRTE. Any refinements or extensions to SRTE required to achieve this work will also be developed and implemented.

In view of the even stronger focus on exploratory research in this phase of the project, compared with Activity III, the work to be accomplished is described in less detail. While the general directions will be in accord with the aims established above, the work descriptions that appear below are only tentative.

8.1 Investigation of Refinements and Extensions of MSDF/STA/RM

This task is divided into four sub-tasks. There is one sub-task for each of the three real-time system components, MSDF, STA, and RM, each dealing with a number of refinements or extensions of concepts developed in Activity III. The fourth sub-task is concerned with extending the framework for an integrated MSDF/STA/RM system for a single ship acting in point defence operations, developed in Activity I, to handle area defence and wide-area multi-platform operations.

8.1.1 Multi-Sensor Data Fusion

8.1.1.1 Refinements of the Single-Platform MSDF Algorithms

This sub-task will review the MSDF sub-system configurations proposed in Subsection 7.1.1 of Activity III, and will select and evaluate the real-time implementations of a sophisticated MSDF sub-system that uses contact level optimal MSDF algorithms such as Multi-Hypothesis Tracking (MHT). Considering that CPF sensors currently provide only track data, this task will first establish the input data requirements from the CPF sensors which would benefit most from such an implementation.

A design for a parallel implementation of this sub-system will be proposed.

8.1.1.2 Multi-Platform Data Fusion

Since the missing capabilities in the existing R&D work of DREV and its contractors are mainly in the area of WATS establishment for multi-platform operations, this area will be given specific emphasis. This sub-task will build on existing capability to fuse Link-11 data and will evaluate all other data sources for the establishment of WATS. There are many issues that need to be investigated before all information from sources outside the platform can be successfully fused, such as data quality, data registration and fusion of data of different qualities (i.e. whether the data can improve positional estimation, or will improve only identification/attribute fusion). This sub-task will propose algorithms to use data of ownship and remote sources to achieve both enhanced tracking and identification performance for producing the onboard tactical situation and compilation of the wide area tactical picture.

To help understand these issues, this sub-task will include a literature survey, which will collect publications, reports and books discussing multi-platform MSDF from all possible aspects, covering its goals, and identifying

the types of data available on the CPF and also on an advanced frigate class ship from remote sources. These results will be used to study the tradeoffs of the computer and fusion architectures and the fusion algorithms that could be used on the CPF and also on an advanced frigate class ship to enhance tracking and identification performance, to establish the wide area tactical situation, and to perform over the horizon tracking.

8.1.1.3 Real-Time Knowledge-Based System for Target Identification

A knowledge-based system for doing air track identification in real time will be designed. The information for this real-time KBS will come from the following eight sources.

1. IFF.

2. ESM.

3. Datalink from friendly air and surface units.

5. Air traffic reports from NORAD.

6. Fire-control radars and surveillance radars.

7. Strategic information (JOTS & MCOIN).

8. Visual information.

9. Daily Task Group Flyops Plans.

The data coming from these sources is often incomplete and uncertain in the sense that multiple identities with different certainty values are obtained for each air track. Real-time uncertainty models for the identity data coming from each sensor will be built and rules to reason about the

separate identities coming from each sensor devised so that contradictions and multiple identities can be eliminated. Research is required on techniques for combining identity data because such data is inherently of a different nature. Some of it is real-time data that is pertinent at the current moment, while other data is strategic and has an associated time lateness attached to it. Rule sets for identifying a large variety of air tracks will be defined, followed by the design of a real-time knowledge-based system for these rule sets, using an anytime algorithm or a design-to-time algorithm approach.

DREV has already used uncertainty reasoning for the air track identification problem in the AIFIE project (Refs. 58-59). The AIFIE models will be studied to see whether they can be used to represent real-time uncertainty in the knowledge-based system.

8.1.2 Situation and Threat Assessment

Research leading to an assessment of the performance of real-time STA models and algorithms in uniprocessor and multiprocessor environments will be conducted. The goal is to develop real-time algorithms for knowledge-based systems and fuzzy expert systems and assess their performance in air defence scenarios.

In this sub-task, the general issues that STA analyses will address include:

- refinement of cluster analysis for multiple ships including situation interpretation for multiple ships;
- development of situation prediction functions including adversarial planning;
- development of functions for monitoring neutrals;
- development of defence assessment functions for multiple ship scenarios;

- effectiveness assessment of softkill weapons; and
- other real-time situation assessment functions.

8.1.2.1 Cluster Analysis and Situation Interpretation for Multiple Platforms

The single ship cluster analysis model of Activity III will be extended to the multiple ship case. An assessment of the significance of each group of tracks for each member of the friendly force will be made. Tracks will be considered based on their grouping by geometric proximity, temporal relations and events, and functional dependence.

The situation interpretation function of the single ship case will be extended to the multiple ship case. In particular, the threat evaluation function of situation interpretation must decide which ship is targeted by anti-ship missiles (or aircraft) in a multiple threat attack on multiple ships. In the multiple ship situation interpretation problem, the CO must know whether he/she is confronted with an aircraft group or a mixed group of air platforms, the mission of the group of platforms, whether these platforms are about to launch anti-ship missiles on his/her ship or other ships and the particular weapons and mode of operation of these weapons used by the platforms against the ships. The anytime and design-to-time algorithms developed for the single ship real-time knowledge-based system will be modified to build a real-time KBS doing situation interpretation for the multiple ship case.

8.1.2.2 Development of Prediction Modules for Situation Assessment: KBSs for Situation Prediction and Hybrid Systems for Adversarial Planning

Situation prediction requires producing a picture of the situation(s) most likely to develop in the near future. When a group of air platforms is identified, the STA sub-system must reason using its internal knowledge and

information from the ship's databases about the most probable offensive actions to be taken by the group (attack using anti-ship missiles, attack in a specially designed attack plan with unguided bombs, etc.).

A variety of techniques will be investigated that provide a short-term prediction of the tactical situation. A situation prediction system using fuzzy logic and fuzzy reasoning, hypothesise and test procedures and explanation-based reasoning within the underlying framework of a real-time KBS will be built. This work will also look at generating trees of possibilities in real time for situation prediction. Knowledge about enemy doctrine, enemy tactics and enemy behaviours will be represented in the situation prediction knowledge bases and appropriate symbolic prediction schemes. The effect of allegiance and the social political context (war or peace) on the prediction scheme used will be investigated.

Real-time implementations of knowledge-based methods for performing situation prediction will be evaluated. These implementations will:

- infer threat actions; and
- predict undetected and future situations.

The feasibility of using case-based reasoning techniques to predict future intentions of the enemy will be determined. Enemy doctrine, tactics and behaviour will be studied to generate the cases used in the scheme. This will also involve determining how to select the most appropriate case among those present. In order to make this scheme into a prediction scheme, time stamps and numerical values will be associated with cases and inferencing methods of nonparametric statistics used to predict future trends of the cases. Finally, to make this approach work in real time, anytime variants of the algorithms employed will need to be developed.

Real-time algorithms using fuzzy rule bases to do threat assessment for the special problem of a group of aircraft that choose interweaving patterns of approach to launch unguided bombs directly on a ship will be developed. Classical threat evaluation algorithms, using CPA and time to reach CPA, are unstable for interweaving aircraft. Neural networks will be investigated for their potential to improve the real-time performance of the fuzzy system.

One of the subfunctions of situation prediction is adversarial planning or enemy plan recognition. Rules or fuzzy rules will be developed to deduce what the enemy's most likely plan is and to judge when changes in enemy behaviour are likely to occur. Such changes can be from surveillance to intrusion, from surveillance to provocation, or from provocation to attack. Real-time AI techniques will be developed to do enemy plan recognition based on a knowledge-based system approach, a fuzzy rule-based system approach, a case-based reasoning approach or some other real-time approach to be identified later.

8.1.2.3 Plan Monitoring for Neutrals

Methods to monitor the behaviour of groups of friendly and neutral units will be developed. There will generally be detailed plans against which the fused picture can be assessed. Groups of neutrals can also be assessed for adherence to expected routes such as air lanes. The methods developed in Subsection 8.1.2.2 for situation prediction will be integrated with those developed here.

8.1.2.4 Defence Assessment

The defence assessment function of situation assessment will be studied. This function is concerned with stationing force assets in the best position to defend against an imminent air attack. Real-time AI structures to solve this problem will be proposed.

8.1.2.5 Effectiveness Assessment of Softkill Weapons

A function to assess in real time the effectiveness of softkill weapons deployed against an air threat will be defined and a real-time rule-based system representation of this function designed. Rule sets will be based on a number of effectiveness assessment techniques such as changes in the radar mode or trajectory of the threat, as well as other techniques identified in the literature.

8.1.2.6 Other Real-Time Situation Assessment Approaches

The feasibility of creating a surveillance function that estimates the enemy's knowledge of the friendly forces will be examined. The latter will be a judgment based on known enemy surveillance, systems derived purely from intelligence data, or a combination of intelligence and recently observed enemy surveillance. The enemy frequently uses situation assessment countermeasures such as concealment, cover or deception to confuse and present a false tactical situation to the friendly forces. Methods to do situation interpretation and situation prediction to overcome these problems will be investigated. In particular, the usefulness of adjoining a truth maintenance system to the real-time KBS situation interpretation and situation prediction components to determine whether information obtained from the enemy is consistent will be studied.

The naval situation assessment problem will also be studied to determine whether there are any other functions of situation assessment not already covered in this sub-task that should be represented by real-time AI structures. In this case, designs for these structures will be proposed.

8.1.3 Resource Management

This sub-task will extend the optimization of single ship warfighting through a number of refinements and extensions of the real-time capabilities of the weapon engagement manager studied in Activity III. This will involve

further work on identifying and analysing advanced concepts, models, algorithms, and architectures for the WEM, including providing support for area defence and wide-area multi-platform operations. The R&D effort will also be expanded to include other aspects of the RM sub-system not covered by the WEM component. Consultations with domain experts from DND is required at various knowledge acquisition phases of the work. The application context will be the CPF, as well as an advanced frigate class ship that is required to conduct point or area defence operations and participate in missions that involve coordinated force-level strategies for engaging the threat. Topics to be addressed include:

- single-ship RM refinements and extensions related to using a multi-function radar and softkill weapons for point defence;
- area defence and multi-ship RM;
- other real-time RM functions, such as sensor management; and
- models, algorithms and architectures.

8.1.3.1 Refinements and Extensions of Single Platform Resource Management

8.1.3.1.1 Impact of Multi-Function Radar

A detailed analysis of the impact of a multi-function radar on the WEM will be undertaken. This study will identify and develop specific strategies, including advanced coordination and scheduling techniques, and their constraints, for using the radar in multi-threat engagements to increase the performance of the WEM. As a preliminary step, a model of a multi-function radar that is sufficiently representative of capabilities and features expected to be present in APAR, and that is adequate as a basis for the identification, development and analysis of these strategies will be developed.

8.1.3.1.2 Resource Management for Softkill Weapons

Knowledge acquisition of techniques, including their operational constraints and limitations, for deploying softkill weapon systems, such as jammers, chaff or flare rockets, rubber ducks, and active decoys, to defend the ship will be conducted. This knowledge will be used to identify and develop appropriate methods for representing and manipulating this knowledge to support real-time decision-making in the use of softkill weapons.

8.1.3.1.3 Integrated Resource Management for Hardkill and Softkill Weapons

After a preliminary knowledge acquisition phase, a detailed analysis of the problems associated with achieving an integration of hardkill and softkill weapon systems will be made. Problems to be identified and analysed include the positive or negative interactions that can result from the concurrent use of both types of weapons. The results of this analysis will be used to develop specific strategies for effecting the integration of these systems. This will lead to identifying various AI- or OR-based methods for reasoning in real time about the merits of the various courses of action available to the Command Team for the combined use of the ship's hardkill and softkill weapon systems. This work will also analyse and compare the advantages and disadvantages of the various approaches to these problems.

8.1.3.2 Area Defence and Multi-Platform Resource Management

All work to this point in the specification and design of the WEM has focused on point defence operations. This work will be reviewed to help identify, propose and develop refinements and extensions that are required to support area defence and wide-area multi-platform operations. Beyond WATS establishment for multi-platform operations, considered in Subsection 8.1.1.2, there is a large number of options for coordinating and controlling the use of force resources to engage the threat, ranging from ships simply acting

autonomously all the way to a comprehensive force-level engagement capability. The work to be conducted here will need to be scoped to the available time and resources, having a view also to anticipated future requirements of the Canadian Navy.

8.1.3.3 Other Real-Time Resource Management Issues

Level 4 in the Joint Directors of Laboratories (JDL) data fusion process model (Ref. 6) deals with process refinements that can be derived from cueing the appropriate sensors and collection sources based on monitoring the performance of MSDF and STA in real time and using this to effect feedback control. One specific resource management problem that arises in such refinements is the sensor management problem, which is concerned with controlling one or more sensors to respond effectively to a changing environment, numerous operator commands, and a variety of functions and missions. The work in this sub-task will identify models and algorithms that are candidates for effecting sensor management in real time. This work will also include a literature survey identifying and describing the various numerical and AI-based techniques that have already been developed to address this problem.

This task will also study the general real-time RM problem to identify: other resources that need to be considered for the development of a fully functional resource manager; appropriate real-time techniques in the literature for addressing these problems; and areas that require further research.

8.1.3.4 Models, Algorithms and Architectures

In this sub-task, the results derived from the work described in Subsections 8.1.3.1 and 8.1.3.2 will be used to specify and design an extended WEM that incorporates functions required to support the Command Team in planning, managing and effecting all engagement actions associated with:

- a multi-function radar;
- hardkill/softkill integration; and
- area defence and some aspects of multi-ship weapon coordination.

All models, algorithms and architectures, as well as the knowledge bases, required to achieve a real-time implementation will be designed, implemented and tested. All work required for this implementation will be conducted in SRTE. It may be necessary to conduct the work described below in Section 8.3 before or in parallel with the experimental work to be accomplished here.

8.1.4 Extended MSDF/STA/RM Integration Framework

In this sub-task, the framework for an integrated MSDF/STA/RM system for a single ship acting in point defence operations, developed in Activity I, will be extended to handle area defence and wide-area multi-platform operations. Aspects to be addressed include identification and definition of data and control flows required to manage the interfaces between multiple platforms in performing multi-platform operations (tactical data link communications to support WATS establishment, etc.), as well as any extensions or refinements that are required in the previous framework.

8.2 Development of an Extended MSDF/STA/RM System

8.2.1 Specification and Design

All the advanced models, algorithms and architectures analysed in Subsections 8.1.1, 8.1.2 and 8.1.3 for the individual MSDF, STA and RM sub-systems, as well as the area defence and multi-platform integration framework developed in Subsection 8.1.4, will be examined to arrive at a preliminary specification of an extended MSDF/STA/RM system, paralleling the work previously done in Subsection 7.1.4.1 for point defence operations. In some of the sections for the individual MSDF, STA or RM processes, many

technologies, such as KBS systems, fuzzy rule-based systems, hybrid systems, and case-based reasoning systems using nonparametric statistics, will be under consideration. A subset of the algorithms and architectural components most likely to succeed in a real-time implementation will be chosen.

8.2.2 Identification of Performance Measures

The generic MOPs, MOEs and real-time system performance measures defined in Sections 5.3 and 5.4 will be considered to identify and derive any additional ones that need to be evaluated for the extended MSDF/STA/RM system.

8.3 Refinement and Extension of SRTE

8.3.1 Specification and Design

The work in this sub-task will identify all extensions of SRTE that are required to specify, design, implement and validate the preliminary specification of an extended MSDF/STA/RM system developed in Subsection 8.2.1.

Should the specification of the extended system require implementation in SRTE of any of a fuzzy rule-based system, a case-based reasoning system with nonparametric statistical inferencing, a hybrid system consisting of a fuzzy rule base and a neural network, or a real-time KBS with a truth maintenance system, the means whereby the required type(s) of system can be implemented as subfunctions of the MSDF/STA/RM system will be identified. Both the acquisition of commercially available software products capable of being integrated into SRTE and the design of a customised shell with the necessary functionality, as a means of extending SRTE's programming capability to include such systems will be considered. The choice will be made based on a determination of the option that leads to the most cost-effective solution.

Based on the extended integration framework developed in Subsection 8.1.4 and on the needs of the extended MSDF/STA/RM system specified in Subsection 8.2.1, the integration framework for a generic MSDF/STA/RM system in SRTE developed in Subsection 6.1.2 will be adapted to enable experimental work in SRTE on the extended system to occur. The necessary extensions to the simulated real-time performance evaluation methodology to support this experimental work will also be made.

Finally, the necessary changes in the original specification and design of SRTE to achieve the required additional capabilities will be made.

8.3.2 Implementation and Validation

In this sub-task, the extended SRTE will be implemented and this implementation will be validated.

8.4 Implementation and Validation of Extended MSDF/STA/RM System in SRTE

The most promising MSDF/STA/RM algorithms and architectural components in the extended MSDF/STA/RM system specified in Subsection 8.2.1 will be selected and implemented. All software implementation and validation of this extended system will be done in the extended SRTE.

8.5 Capture of Real-Time Requirements for Extended MSDF/STA/RM System

Finally, a detailed analysis of the differences in performances and capabilities between the baseline and extended MSDF/STA/RM systems will be made. These assessments will be used to identify and propose promising areas for follow-on research in MSDF/STA/RM system design.

9.0 CONCLUSIONS

Previous DREV R&D in the various levels of data fusion and sensor and weapon management have approached the problem of satisfying perceived future shipboard CCS data and information processing requirements in an essentially discrete, bottom-up manner. The viability of the various concepts being investigated in this R&D for implementation in real time has also received little attention. This previous research has certainly provided essential pieces of the puzzle. However, there are other important pieces which must now be added to complete the picture.

To address this, the Data Fusion and Resource Management (DFRM) group at DREV has developed an approach to help counter the anticipated threat to our surface ships by increasing the AWW defence capability of Canadian Patrol Frigates (CPFs) through the development of a real-time, embedded decision support system (DSS) that interacts with combat system operators to support the tactical decision making and action execution processes in a ship's Operations Room. Among its principal roles, this DSS will: continuously take in data from the ship's sensors and other information sources; support the formulation, maintenance and display of an accurate dynamic tactical picture of the AWW derived by fusing all available data, and thereby assist in the interpretation of the evolving tactical situation; formulate and provide recommended courses of action for responding to anticipated or actual threats, including, as necessary, options to defend the ship using the best possible combination of hardkill and softkill weapons or other defensive means; present all necessary information to enable the Commanding Officer (CO) and AWW team to decide on a course of action in a timely manner; and coordinate and direct action implementation once a decision to act has been made and an action is being carried out. The DSS will be an embedded component of the ship's combat system, integrated within the CCS system, that provides real-time implementations of functions for Multi-Sensor Data Fusion (MSDF), Situation and Threat Assessment (STA), and Resource Management (RM). In view of the functional

integration involved, this sub-system of the ship's CCS is referred to as an MSDF/STA/RM system.

In parallel with continuing efforts within the DFRM group to effect refinements, improvements and extensions in individual data fusion and resource management processes, the SRTE project has been initiated with the new focus of addressing their integration in a top-down manner and at evaluating potential solutions for the design of an MSDF/STA/RM system.

However, with expanded capability comes increased system complexity. The greatly expanded system complexity implied by the need to integrate MSDF, STA and RM system components makes it extremely difficult to explore and validate the feasibility of design concepts and capture the real-time requirements of such a large, complex, distributed real-time system. This problem is compounded by the requirement on such a system to perform effectively in a wide range of settings, with concomitant stringent demands on performance. It is likely, for example, that such integration may require vastly greater computing capabilities than are present in the current generation of naval surface combatants if satisfactory, predictable and robust real-time behaviour of the integrated system is to be achieved. Questions of identifying how much additional computational capability is required and where, as well as the benefits to the CCS to be derived from such increased capability, are important issues that need to be addressed.

The approach being pioneered in the SRTE project for attacking the complexity of this design problem involves a major effort aimed at developing the required tools for deriving answers to system design questions. Specifically, this involves the design and implementation of an environment, called the Simulated Real-Time Environment (SRTE), for evaluating concepts, algorithms and architectures for MSDF/STA/RM. In this highly novel approach, all real-time system development and experimentation is conducted on a simulator running on a host architecture whose purpose is to capture the functional requirements, temporal behaviour and real-time performance of the MSDF/STA/RM integration. The simulation engine in the

proposed environment will simulate the real-time execution of the automated components of the MSDF/STA/RM system running on a user configured target hardware architecture. The target could be a single parallel machine or a collection of (heterogeneous) machines connected via a local area network (LAN). Both open-loop and closed-loop analyses of system behaviour will be achievable. This environment will permit debugging, testing and non-intrusive performance monitoring of MSDF/STA/RM code.

The level of detail that will be available in SRTE permits an unprecedented ability not just to uncover situations in which automated system performance breaks down, but also to reveal exact causes, and - because the simulation maintains a complete picture of system events - to suggest remedial action. Moreover, since the automated system is only being simulated, fixes to problems can be attempted immediately, and their success and side-effects evaluated speedily.

The high-level aim of the SRTE project is to capture and analyse the real-time requirements of a CCS integrating MSDF, STA and RM into a system using all information available on the current (and to some extent the future or upgraded) ship. While the immediate focus is the CPF platform, it is also likely that the concepts, techniques and algorithms to be developed in the SRTE project could apply to the improvement of the CCS of a TRUMP platform or for determining CCS requirements for the expected replacement of this class of ship in the next century.

An important goal of this project is to help support risk mitigation in the design of the next generation of the CPF's CCS. An initial step in exploring MSDF, STA and RM concepts in this project will therefore concern the development of a baseline MSDF/STA/RM system. The objective is to develop an integrated real-time system that provides an enhanced CCS for the CPF. This includes an improved target surveillance and tracking capability and an improved Threat Evaluation and Weapon Assignment (TEWA) capability. Then, in a later phase, these concepts will be refined and extended (e.g., more sophisticated sensor fusion techniques, a more complete

situation assessment capability, the inclusion of softkill weapons in the resource management model, etc.) in order to investigate some multiple platforms issues.

Finally, it is important to note that a comprehensive study of cognitive systems engineering issues in the design of an MSDF/STA/RM-based decision support system that examines technological and cognitive issues jointly remains to be performed. An initial step toward this was described in Chapter 3.0. However, as indicated there, there are a number of human-machine system issues that need to be further explored and new work to be undertaken toward the design of an MSDF/STA/RM system. This includes modelling human/team expertise, competence and performance in Operations Room activities, and using this knowledge to define a model of cooperation between human decision makers and the automated system, as well as capturing cognitive system requirements from the perspective of potential future users of the support system. Various measures to initiate work that examines these issues are currently being investigated, as part of the SRTE project and/or by other means outside the scope of this project.

10.0 REFERENCES

1. Ousborne, D.R., "Ship Self-Defense Against Air Threats", Johns Hopkins Technical Digest, Vol. 14, No. 2, pp. 125-140, 1993.

2. O'Keefe, S., Kelso, F., and Mundy, C., "... From the Sea: Preparing the Naval Service for the 21st Century", Proceedings: Naval Institute, Vol. 118, No. 11, pp. 93-96, 1992.

3. CFCD 117, Vol. II, Promulgation of Maritime Command's Doctrine and Requirements for Command and Control, September, 1995.

4. Roy, J., Chalmers, B., Carling, R., and Bossé, É., "Overview of Shipboard Data Fusion and Resource Management R&D Results and Rationale for its Real-Time Implementation in the ASCACT Testbed", DREV-TM-9518, April 1996, UNCLASSIFIED

5. Llinas, J. and Waltz, E.L., "Multi-Sensor Data Fusion", Artech House, Norwood, MA, 1990.

6. DFDS Panel, "Functional Description of the Data Fusion Process", Data Fusion Development Strategy Panel, Document Prepared for the Office of Naval Technology (ONT) Data Fusion Development Strategy, November 1991.

7. Flach, J., Hancock, P., Caird, J., and Vicente, K., Global Perspectives on the Ecology of Human-Machine Systems, Lawrence Erlbaum Associates, Publishers, Hillsdale, New Jersey, 1995.

8. Mitroff, I. and Featheringham, T.R., "On Systematic Problem Solving and the Error of the Third Kind", Behavioral Science, Vol. 19, pp. 383-393, 1974.

9. Woods, D.D., "Cognitive Technologies", The AI Magazine, Vol. 6, No. 4, pp. 86-92, 1986.

10. Endsley, M.R., "Towards a New Paradigm for Automation: Designing for Situation Awareness", paper presented at the 6th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems, Cambrudge, MA, June 27-29, 1995.

11. Woods, D.D. and Roth, E.M., "Cognitive Systems Engineering", in Handbook of Human-Computer Interaction, M. Helander, ed., Elsevier Science Publishers B.V., North-Holland, pp. 3-43, 1988.

12. Woods, D.D., "Coping with Complexity: The Psychology of Human Behaviour in Complex Systems", in Mental Models, Tasks and Errors, L.P. Goodstein, H.B. Andersen, and S.E. Olsen, eds., Taylor and Francis, pp. 128-148, 1988.

13. Klein, G.A., Orasanu, J., Calderwood, R., and Zsambok, C.E., eds., Decision Making in Action, Ablex Publishing Corporation, Norwood, New Jersey, 1993.

14. Klein, G.A., "Naturalistic Models of C^3 Decision Making", in Science of Command and Control: Coping with Uncertainty, S.E. Johnson and A.H. Levis, eds., AFCEA International Press, Washington, D.C., pp. 86-92, 1988.

15. Klein, G.A., "Recognition-Primed Decisions", in Advances in Man-Machine Systems Research, W.B. Rouse, ed., Vol. 5, Greenwich, CT, JAI Press Inc., pp. 47-92, 1989.

16. Woods, D.D., "Paradigms for Intelligent Decision Support", in Intelligent Decision Support in Process Environments, E. Hollnagel et al., eds., NATO ASI Series, Vol. F21, Springer-Verlag, Berlin, pp. 153-173, 1986.

17. Klein, G.A. and Calderwood, R., "Decision Models: Some Lessons from the Field", IEEE Transactions on Systems, Man, and Cybernetics, Vol. 21, No. 5, pp. 1018-1026, 1991.

18. Foster, G.D., "Contemporary C^2 Theory and Research: the Failed Quest for a Philosophy of Command", Defence Analysis, Vol. 4, No. 3, pp. 201-228, 1988.

19. Wohl, J.G., "Force Management Decision Requirements for Air Force Tactical Command and Control", IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-11, No. 9, 1981.

20. Hart, G. and Lind, W.S., America Can Win: the Case for Military Reform, Adler and Adler, Bethesda, Maryland, 1986.

21. Military Operations Research Society, Command and Control Evaluation Workshop, Military Operations Research Society, Alexandria, Virginia, 1985.

22. M/A-Com Linkabit, Inc. National Defense University (NDU) Command and Control Research Program (CCRP), Technical Report 158, M/A-Com Linkabit, Inc., Vienna, Virginia, 1985.

23. Lawson, J.S., "The State Variables of a Command and Control System", in J. Hwang, ed., Selected Analytical Concepts in Command and Control, pp. 61-83, Gordon and Breach, New York, 1982.

24. Klein, G., "The Value Added by Cognitive Task Analysis", Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting, pp. 530-533, 1995.

25. Rasmussen, J., Information Processing and Human Machine Interaction: An Approach to Cognitive Engineering, North-Holland, New York, 1986.

26. NATO, "COADE: A Framework for Cognitive Analysis, Design and Evaluation", Technical Report AC/243(Panel 8)TR/17, Defence Research Group, NATO HQ, Brussels, 1995.

27. Kaempf, G.L., Wolf, S., and Miller, T.E., "Decision Making in the AEGIS Combat Information Center", Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, pp. 1107-1111, 1993.

28. Hammond, K.R., Hamm, R.M., Grassia, J., and Pearson, T., "Direct Comparison of the Efficacy of Intuitive and Analytical Cognition in Expert Judgment", IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-17, No. 5, pp. 753-770, 1987.

29. Hammond, K.R., "Judgment and Decision Making in Dynamic Tasks", Information and Decision Technologies, Vol. 14, pp. 3-14, 1988.

30. Endsley, M.R., "Toward a Theory of Situation Awareness in Dynamic Systems", Human Factors, Vol. 37, No. 1, pp. 32-64, 1995.

31. Hutchins, S.G. and Kowalski, J.T., "Tactical Decision Making Under Stress: Preliminary Results and Lessons Learned", Proceedings of the 10th Annual Conference on Command and Control Decision Aids, Washington, D. C., pp. 85-96, 1993.

32. Hutchins, S.G. and Rummel, B.K., "A Decision Support System for Tactical Decision Making Under Stress", Proceedings of the First International Conference on Command and Control Research and Technology, Washington, D. C., pp. 163-173, 1995.

33. Hutchins, S.G., "Principles for Intelligent Decision Aiding", to appear in Human Interaction with Complex Systems, E. H. Park, ed., Kluwer Academic Publishers, Norwell, Massachusetts, 1996.

34. Roth, E.M. and Woods, D.D., "Aiding Human Performance I : Cognitive

Analysis", Le Travail Humain, Vol. 51, No. 1, pp. 39-64, 1988.

35. Zachary, W. and Zaklad, A., "Stress Effects on Tactical Decision Performance in Ship-Based Antiair Warfare", Technical Document 2443, CHI Systems Inc., 1993.

36. Wickens, C.D. and Flach, J.M., "Information Processing", in Human Factors in Aviation, E.L. Wiener and D.C. Nagel, eds., Academic Press, Inc., San Diego, pp. 111-155, 1988.

37. Tversky, A. and Kahneman, D., "Judgment under Uncertainty: Heuristics and Biases", Science, Vol. 185, pp. 1124-1131, 1974.

38. Endsley, M.R. and Kiris, E.O., "The Out-of-the-Loop Performance Problem and Level of Control in Automation", Human Factors, Vol. 35, No. 2, pp. 381-394, 1995.

39. Rouse, W.B., "Human-Computer Interaction in the Control of Dynamic Systems", Computing Surveys, Vol. 13, No. 1, pp. 71-99, 1981.

40. Endsley, M.R., "Towards a New Paradigm for Automation: Designing for Situation Awareness", paper presented at the 6th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems, Cambridge, Massachusetts, June 27-29, 1995.

41. Muir, B.M., "Trust Between Humans and Machines, and the Design of Decision Aids", in Cognitive Engineering in Complex Dynamic Worlds, E. Hollnagel, G. Mancini, and D.D. Woods, eds., Academic Press, Harcourt Brace Jovanovich, Publishers, London, pp. 71-83, 1988.

42. Thayer, R.H. and Dorfman, M., eds., System and Software Requirements Engineering, IEEE Computer Society Press, Los Alamitos, California, 1990.

43. Laplante, P., Real-Time Systems Design and Analysis: An Engineer's Handbook, IEEE Computer Society Press, Los Alamitos, California, 1993.

44. Bucci, G., Campanai, M., and Nesi, P., "Tools for Specifying Real-Time Systems", Real-Time Systems, Vol. 8, pp. 117-172, 1995.

45. Roy, J.M.J. and Bossé, É., "Definition of a Performance Evaluation Methodology for Sensor Data Fusion Systems", DREV-R-9423, September 1995, UNCLASSIFIED

46. Roy, J.M.J., Bossé, É., and Dion, D., "CASE_ATTI: An Algorithm-Level Testbed for Multi-Sensor Data Fusion", DREV-R-9411, May 1995, UNCLASSIFIED

47. Thomson CSF Systems Canada, "Software Requirements Specification for the Development Environment of the Anti-Air Warfare Simulator", DSS Contract No.W7701-0-3202/01-XSK, TCSC File No.: G0456C-01, August 1991.

48. Thomson CSF Systems Canada, "Software Requirements Specification for the Simulation Framework of the Anti-Air Warfare Simulator", DSS Contract No. W7701-0-3202/01-XSK, TCSC File No.: G0456C-02, August 1991.

49. Thomson CSF Systems Canada, "Software Requirements Specification for the Modelled Entities/TEWA of the Anti-Air Warfare Simulator", DSS Contract No. W7701-0-3202/01-XSK, TCSC File No.: G0456C-03, February 1992.

50. Covington, R.G., Dwarkadas, S., Jump, J.R., Lauderdale, G., Madala, S., and Sinclair, J.B., The Efficient Simulation of Parallel Computer Systems, Technical Report TR 8904, Department of Electrical and Computer Engineering, Rice University, Houston, Texas, 1990.

51. Goldschmidt, S.R., Simulation of Multiprocessors: Accuracy and Performance, Ph.D Thesis, Department of Electrical Engineering, Stanford University, California, 1993.

52. Brewer, E. A., Dellarocas, C. N., Colbrook, A., and Weihl, W. E., Proteus: A High-Performance Parallel-Architecture Simulator, Technical Report MIT/LCS/TR-516, Laboratory for Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1991.

53. Dellarocas, C. N., A High-Performance Retargetable Simulator for Parallel Architectures, Master's Thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1991.

54. Brewer, E. A. and Dellarocas, C. N., Proteus User Documentation, Version 0.5, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 1992.

55. Boothe, B., "Fast Accurate Simulation of Large Shared Memory Multiprocessors", Proceedings of the Twenty-Seventh Annual Hawaii International Conference on System Sciences, pp. 251-260, 1994.

56. Chalmers, B.A., "An Adaptive Planner in a Layered Real-Time Architecture for an Engagement Manager in a Naval Threat Evaluation and Weapon Assignment System: An Overview", DREV R-4768, July 1994, UNCLASSIFIED

57. Chalmers, B.A. and Da Ponte, P., "MIMD Algorithms for Naval Resource Planning: Overview and Preliminary Assessment", DREV R-9420, November 1995, UNCLASSIFIED

58. Paramax Systems Canada, "Investigations of Attribute Information Fusion Techniques for Estimating Target Identity (Volume 1): Task II and Task III", Paramax-SSC Contract Number: W7701-2-0400/01-XSK, Paramax DM No: 112000025, 06 October 1993, UNCLASSIFIED.

(DREV Scientific Authority: L. Des Groseilliers)

59. Paramax Systems Canada, "Investigations of Attribute Information Fusion Techniques for Estimating Target Identity (Volume 2): Task IV and Task V", Paramax-SSC Contract Number: W7701-2-0400/01-XSK, Paramax DM No: 112000025, 6 October 1993, UNCLASSIFIED. (DREV Scientific Authority: L. Des Groseilliers)

UNCLASSIFIED

INTERNAL DISTRIBUTION

DREV - R - 9629

1 - Deputy Director General
6 - Document Library
1 - B. Chalmers (author)
1 - J.M.J. Roy (author)
1 - R. Carling (author)
1 - S. Paradis (author)
1 - É. Bossé (author)
1 - G. Picard
1 - G. Otis
1 - LCdr S. Dubois
1 - Capt F. Beaupré
1 - J.-C. Labbé
1 - P. Labbé
1 - J.-C. St-Jacques
1 - L. Lamontagne
1 - M. Bélanger
1 - D. Gouin
1 - R. Charpentier
1 - G. Thibault
1 - D. Thibault

EXTERNAL DISTRIBUTION (cont'd)

DREV - R - 9629

5 - DREO;
Attn: D. Liang
P. Yansouni
A. Bridgewater
D. Dyck
B. Ford

1 - PMO CPF

1 - PMO TRUMP

1 - PMO Aurora

1 - PMO Aurora;
Attn: Maj G.L.J. Gélinas

1 - PMO Aurora;
Attn: Capt J.Y.J.R. Létourneau

1 - PMO Aurora;
Attn: Capt J.J.D. Lavoie

1 - PMO NWS

1 - NETE;
Attn: Commanding Officer

1 - NETE;
Attn: S. Roy

1 - Canadian Forces Command and Staff College;
Toronto
Attn: Commanding Officer

1 - Canadian Forces School of Aerospace Studies;
CFB Winnipeg
Westwin, Manitoba
R3J 0T0
Attn: Commanding Officer

1 - CF Maritime Warfare Centre;
CFB Halifax
Halifax, Nova Scotia
Attn: Commanding Officer

EXTERNAL DISTRIBUTION

DREV - R - 9629

1 - DRDIM
1 - DRDIM (unbound copy)
1 - DRDB
1 - MARCOM N6
1 - DMSS
2 - DMSS - 6
1 - DMSS - 8
1 - DMSS - 8 - 2
1 - DMSS - 8 - 8
1 - DMSS - 8 - 8 - 2
1 - DMFD
1 - DMOR
1 - DNR
2 - DNR - 4
1 DNR - 4 - 2
1 DNR - 4 - 4
1 DNR - 4 - 6
1 - DRDCS
1 - DRDCS - 4
1 - DRDCS - 5
2 - DSAM
1 - DSAM - 2
2 - DCIEM;
Attn: R. Pigeau
C. McCann
2 - DREA;
Attn: A. Ashley
M. McIntyre

EXTERNAL DISTRIBUTION (cont'd)

DREV - R - 9629

1 - NEU(A);
Attn: CSEO

1 - NEU(P);
Attn: CSEO

1 - CFNOS;
Attn: Commanding Officer

1 - CFNES;
Attn: Commanding Officer

2 - Defence Science and Technology Organization;
P.O. Box 1500
Salisbury, South Australia 5108
Australia
Attn: D.J. Kewley
M. Nelson

1 - TNO Physics and Electronics Laboratory;
Oude Waalsdorperweg 63
P.O. Box 96864
2509 JG The Hague
The Netherlands
Attn: H.E. Keus

7 - Lockheed Martin Electronic Systems Canada;
6111 Royalmount Avenue
Montréal, Québec
H4P 1K6
Attn: E. Shahbazian
J.-R. Duquet
D. Blodgett
P. Bergeron
J. Couture
M. Macieszczak
M. Mayrand

UNCLASSIFIED

SECURITY CLASSIFICATION OF FORM
(Highest classification of Title, Abstract, Keywords)

DOCUMENT CONTROL DATA

1. ORIGINATOR (name and address) DREV 2459 Pie XI Blvd North Val-Bélair, Qc G3J 1X5	2. SECURITY CLASSIFICATION (Including special warning terms if applicable) UNCLASSIFIED

3. TITLE (Its classification should be indicated by the appropriate abbreviation (S,C,R or U)

Requirements Capture and Design Issues for a Real-Time Decision Support System for the Canadian Patrol Frigate

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

CHALMERS, B., ROY, J., CARLING, R., PARADIS, S. and BOSSÉ, É.

5. DATE OF PUBLICATION (month and year)	6a. NO. OF PAGES	6b. NO. OF REFERENCES
1998	119	59

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. Give the inclusive dates when a specific reporting period is covered.)

Report

8. SPONSORING ACTIVITY (name and address)

DREV

9a. PROJECT OR GRANT NO. (Please specify whether project or grant)	9b. CONTRACT NO.
1ba12	N/A

10a. ORIGINATOR'S DOCUMENT NUMBER	10b. OTHER DOCUMENT NOS.
DREV-R-9629	N/A

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

- [X] Unlimited distribution
- [ ] Contractors in appoved countries (specify)
- [ ] Canadian contractors (with need-to-know)
- [ ] Government (with need-to-know)
- [ ] Defence departments
- [ ] Other (please specify) :

12. DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in 11) is possible, a wider announcement audience may be selected.)

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual).

DREV initiated the Simulated Real-Time Environment (SRTE) project to investigate concepts and capture the real-time requirements of a decision support system that can provide enhanced capability within the Command and Control System to counter the current and anticipated future air and surface threat to the Canadian Patrol Frigate. Among its principal roles, this system will: continuously take in data from the ship's sensors and other information sources; support the formulation, maintenance and display of an accurate tactical picture derived by fusing all available data, and display of an accurate tactical picture derived by fusing all available data, and assist in the interpretation of this picture; and formulate and provide recommended courses of action for responding to anticipated or actual threats. This document describes both cognitive and technological aspects of the decision aid approach that is a cornerstone of the SRTE project and gives a detailed technical description of the methodology and associated R&D work that is being conducted to capture system requirements.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each sould be indicated as with the title.)

Multi-Sensor Data Fusion
Situation Assessment
Threat Assessment
Resource Management
Decision Making
Decision Support System
Situation Awareness
Cognitive Systems Engineering
Task Analysis
Simulation
Real-Time Requirements
Decision-Making Requirements

507675

(DCD03E.IFD - 95.02.22)